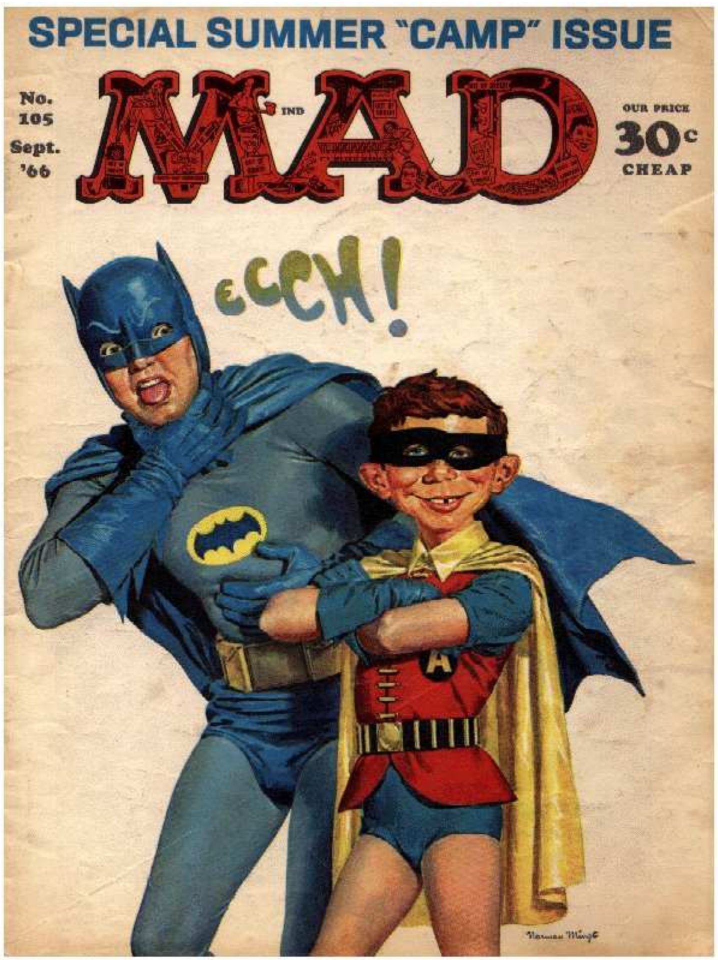
Plans for Kaon Physics at BNL

The dynamic duo: $K^+ \to \pi^+ \nu \overline{\nu}$ & $K_L \to \pi^0 \nu \overline{\nu}$



HIF04. June 5-8, 2004

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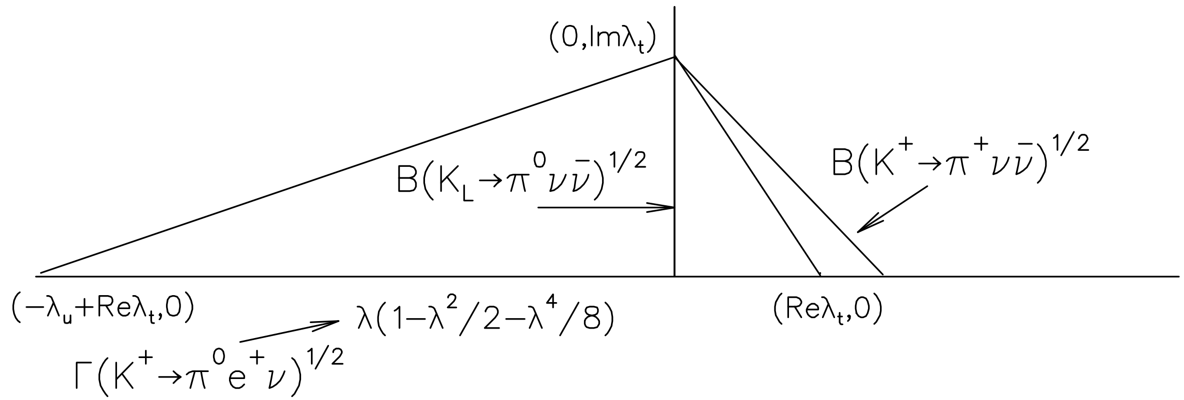
Brookhaven National Laboratory

Introduction

The kaon unitarity triangle:

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0 \qquad \text{or } \lambda_\mathrm{u} + \lambda_\mathrm{c} + \lambda_\mathrm{t} = 0$$



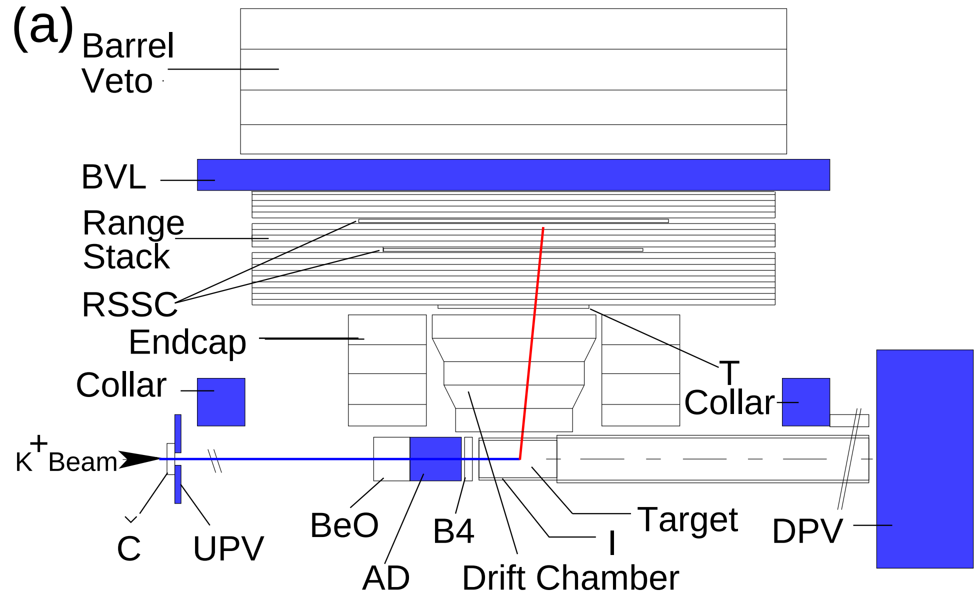
- $K \to \pi\nu\overline{\nu}$ and $K^+ \to \pi^0 e^+ \nu$ decays completely determine the UT.
- $K_L \to \pi^0\nu\overline{\nu}$ provides direct measurement of triangle area (J_{CP}, "the price of CP violation" in the quark sector). Theoretical uncertainty on BR ~ 2%.
- $K^+ \to \pi^+\nu\overline{\nu}$ probes both real and imaginary parts of λ_t. BR uncertainty (th) ~ 7%. Buras: NNLO QCD calculation should reduce this to ~ 2% (hep-ph/0405132)
- Comparison with UT determination from B sector will be a powerful tool to try to unravel the flavor dynamics
- The future of kaon physics at BNL will be primarily centered on measuring this "dynamic duo": $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L \to \pi^0\nu\overline{\nu}$.

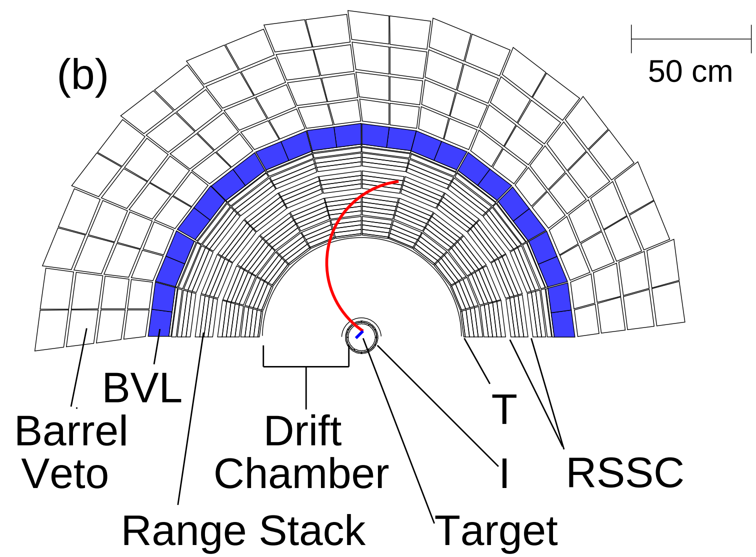
$K^+ \to \pi^+ \nu\overline{\nu}$

- Std. Model expectation: $(0.78 \pm 0.12) \times 10^{-10}$ (hep-ph/0405132)
- BNL E787 (1995-98) observed 2 $K^+ \to \pi^+ \nu\overline{\nu}$ candidates with a background of 0.15 ± 0.05 events
- Likelihood analysis based on additional signal/bkg discrimination yielded:
  - Probability of bkg alone giving rise to these 2 (or "cleaner") events = 0.0014.
  - BR($K^+ \to \pi^+ \nu\overline{\nu}$) = $1.57^{+1.75}_{-0.82} \times 10^{-10}$.
- E787 was primarily limited by proton flux from AGS on K production target.
- E949 is based on "modest" upgrades to the E787 program.
  - Use "entire" proton flux. 15×10^{12} p/spill $\to 65 \times 10^{12}$
  - Longer AGS running during RHIC operation (≥ 25 weeks/yr)
  - Detector upgrades: photon veto, π^+ tracking and kinematic resolution, trigger/DAQ, K^+ tracking system
- Aimed at SES$\leq 10^{-11}$ or 5-10 SM events

Recall E787/E949 technique

- Incoming beam ($\sim 700 MeV/c$) tagged by Cerenkov, dE/dx counters.
- Stopped kaon beam. Delayed coincidence cut against scattered beam π. High geometrical acceptance.
- Stopped decay pion. Redundant measurements of kinematics. Observation of $\pi \to \mu \to e$ decay sequence for μ rejection.
- Photon veto counters surround everything. Minimize inactive material.



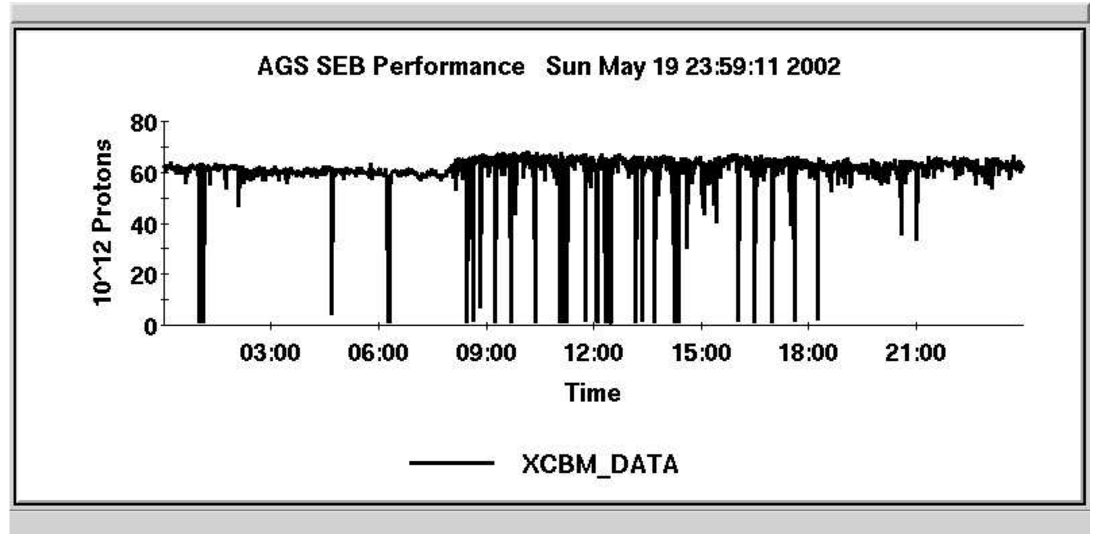


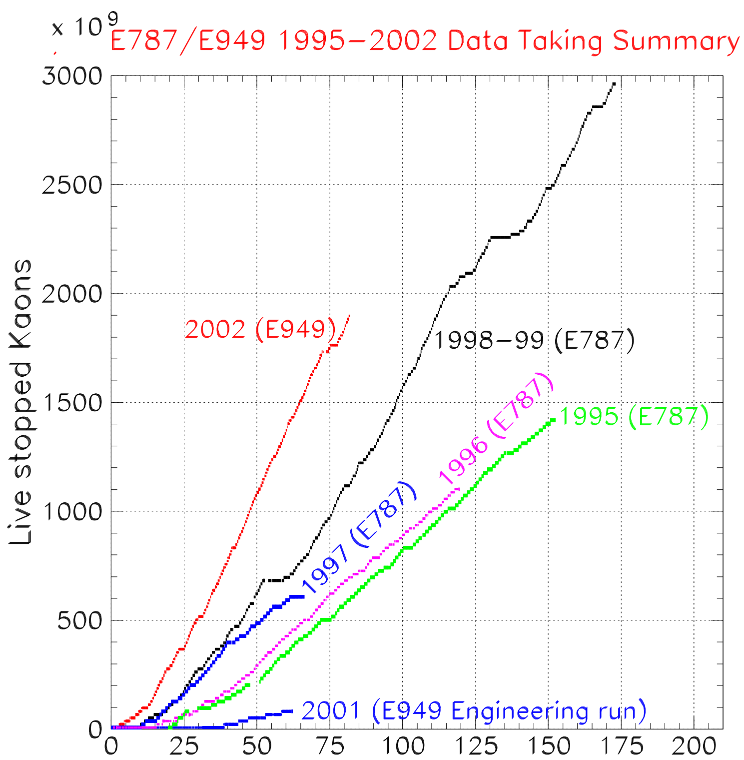
BNL E949: Beam

Proton intensity:

- 76×10^{12}/spill (peak)
- 65×10^{12}/spill (typical)

E949 (2002) protons on target (typical day)



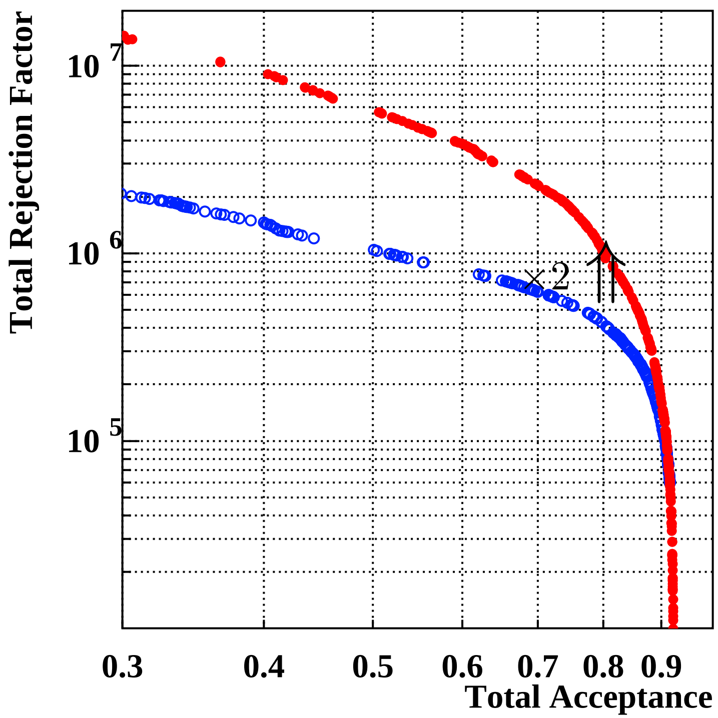


Not optimal in 2002:

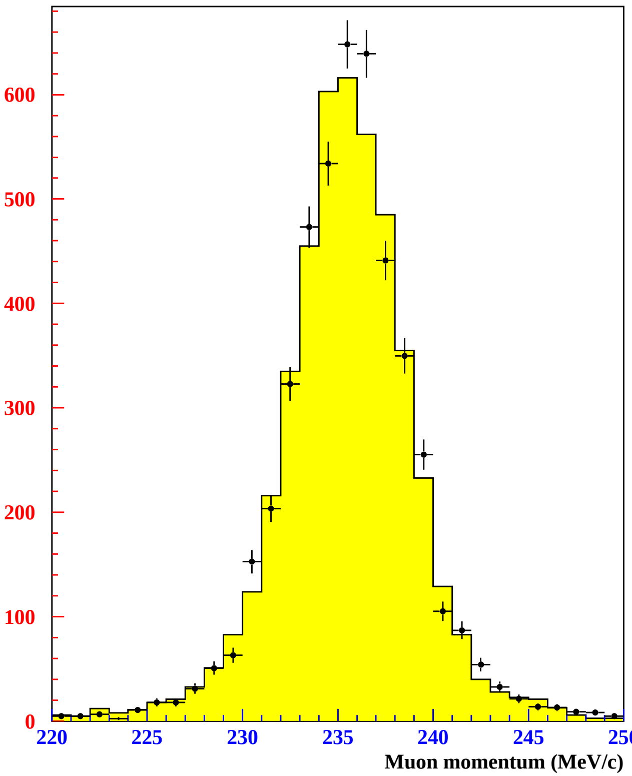
- Short run (see plot at left)
- AGS main power supply problem. Lower proton momentum $\Rightarrow\sim 10\%$ loss in K flux. 20% worse duty factor compared to E787
- K/π separator problems

BNL E949: Detector upgrades

PV rejection (E787 & E949)



E949 momentum resolution



- Photon veto: $\times 2$ more rejection at nominal acceptance
- Comparable momentum resolution at $\times 2$ instantaneous rate

Offline analysis

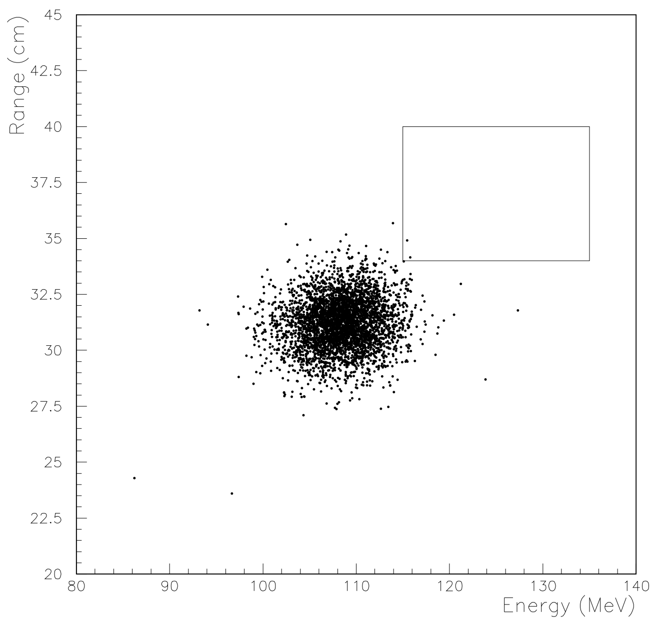
Robust estimate of background at < 1 event level

- Blind analysis
  - Signal region is hidden (by inverting cuts) while cuts are developed and background levels estimated
  - Cuts against background developed with uniformly sampled subset of data. Effect of cuts is measured (once) in an unbiased way on remainder of data.
- "Bifurcated" analysis
  - A priori identification of background sources
  - Same dataset for background studies and signal search
  - Two independent cuts with high rejection for each background
  - Measurement of background levels in the signal region at the $10^{-3} - 10^{-2}$ level
- Correlation studies
- Prediction of background levels around signal region (followed by measurement)
- Likelihood analysis (using predetermined likelihood functions) in the signal region for assessing candidate events.
- New in E949. More confidence in the likelihood technique, and shifting philosophy from "discovery mode" to "measurement mode". $\Rightarrow$ open up the signal region (more background) and rely on likelihood analysis for BR.

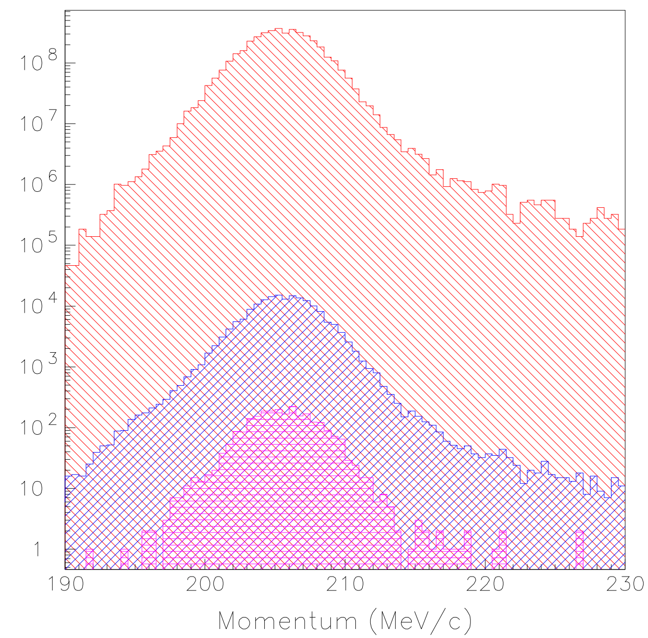
“Bifurcated” analysis

$K^+ \to \pi^+\pi^0$ background as an example:

Events tagged with presence of γs



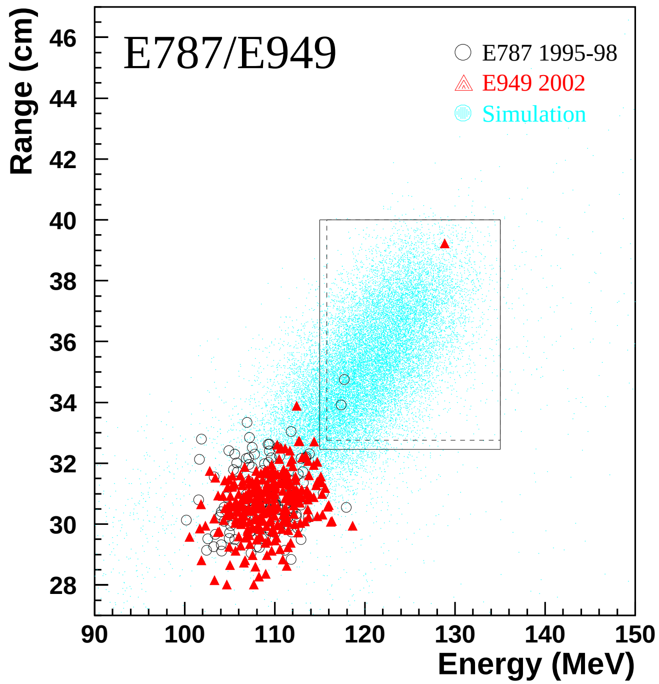
Events tagged by $K_{\pi 2}$ kinematics



$$N_{bkg} = \frac{N}{R_{PV} - 1}$$

$K^+ \to \pi^+\nu\overline{\nu}$. First result from E949

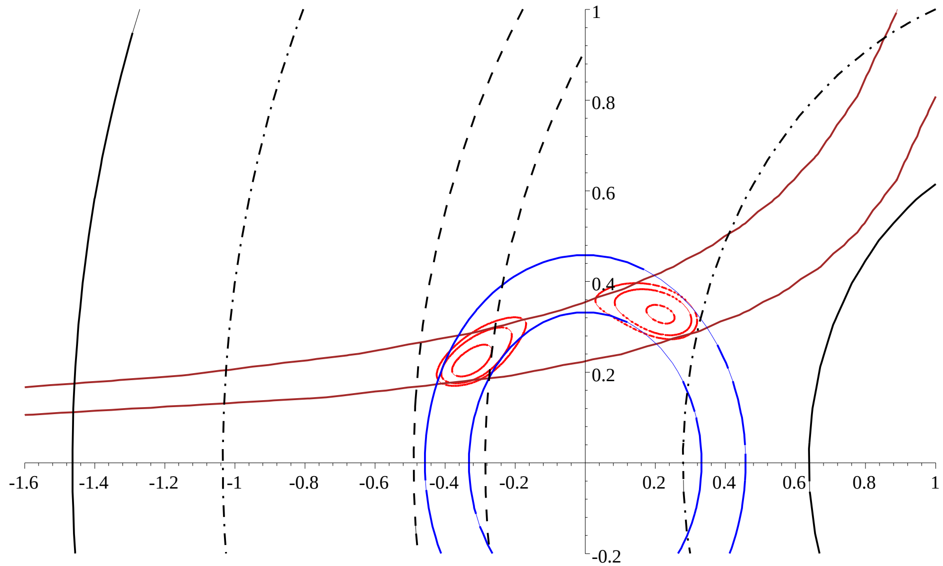
E949 (2002) + E787(95-98)



	E787		E949
N_K	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	1995A	1998C	2002A
S_i/b_i	50	7	0.9
W_i	0.98	0.88	0.48
Background Prob.	0.006	0.02	0.07

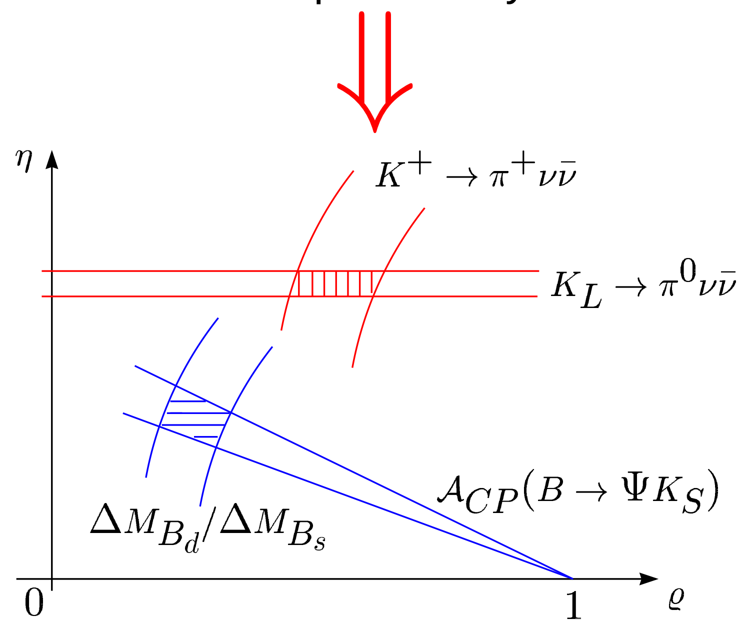
- BR($K^+ \to \pi^+\nu\overline{\nu}$) = $(0.96^{+4.09}_{-0.47}) \times 10^{-10}$ (E949 alone)
- BR($K^+ \to \pi^+\nu\overline{\nu}$) = $(1.47^{+1.30}_{-0.89}) \times 10^{-10}$ (E787+E949)
- Std Model expectation: BR($K^+ \to \pi^+\nu\overline{\nu}$) = $(0.78 \pm 0.12) \times 10^{-10}$ (hep-ph/0405132)
- Backgrounds under good control, determined almost entirely from the data
- Ready/waiting to take more data (12 weeks in 2002; proposal: 60 weeks)

$K^+ \to \pi^+\nu\overline{\nu}$. Impact on unitarity triangle



(figure courtesy G. Isidori)

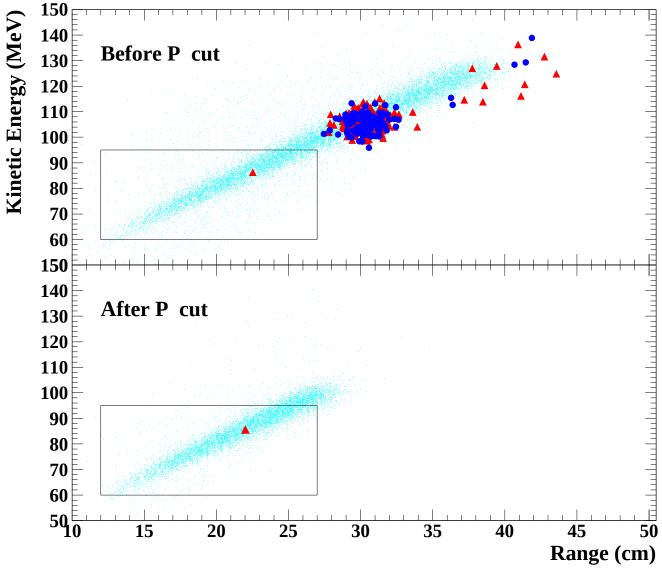
Perhaps one day?



- Remove B-mixing constraints from UT (assume new physics is present in B-mixing)
- Dark circles show constraints from BR($K^+ \to \pi^+\nu\overline{\nu}$)
- Obviously needs more statistics

$K^+ \to \pi^+\nu\overline{\nu}$. Other recent results

New E787 result on kinematic region below $K^+ \to \pi^+\pi^0$ peak from analysis of 1997 data



	E787 (1996)	E787 (1997)
N_K	1.12×10^{-12}	0.61×10^{-12}
Total Acceptance	7.65×10^{-4}	9.7×10^{-4}
Total Background	0.73 ± 0.18	0.49 ± 0.16
# events seen	1	0

- E787(96+97): BR($K^+ \to \pi^+\nu\overline{\nu}$) $< 2.2 \times 10^{-9}$ ($p_\pi < 195$ MeV/c) $\Rightarrow$ $\times 2$ improvement
- Backgrounds more difficult ($K^+ \to \pi^+\pi^0$ with π^+ scatter in K stopping target; π^0 heads towards region of weak photon coverage)
- Photon veto is improved in E949. Improvement in barrel region already demonstrated in analysis above $K^+ \to \pi^+\pi^0$ peak. Improvement in beam region (crucial for this analysis) remains to be seen. Other ideas to increase acceptance (or rejection) under study.

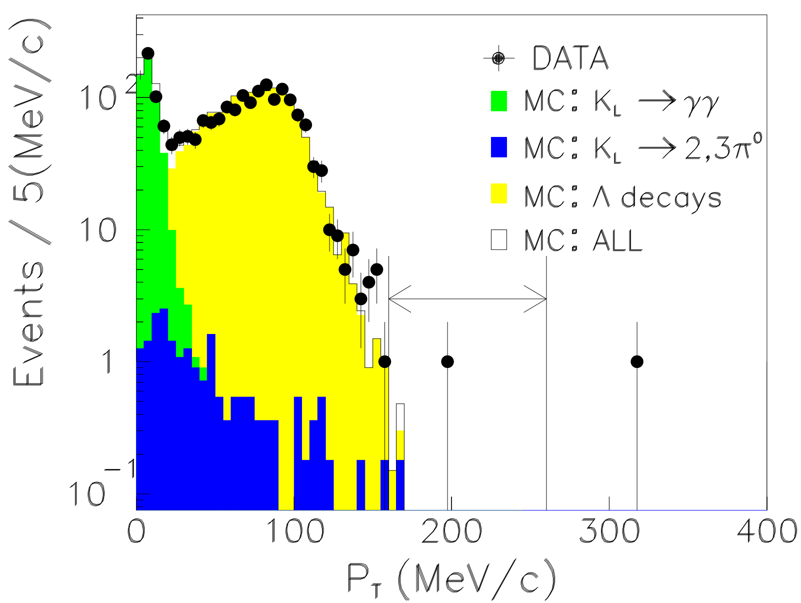
$K_L \to \pi^0 \nu\overline{\nu}$

- Std. Model expectation: $(0.30 \pm 0.06) \times 10^{-10}$ (hep-ph/0405132)
- Grossman-Nir bound:

$$\frac{BR(K_L \to \pi^0 \nu\overline{\nu})}{BR(K^+ \to \pi^+ \nu\overline{\nu})} < \frac{\tau_L}{\tau_+} \times \frac{1}{r_{is}} \sim 4.4$$

$$or\ BR(K_L \to \pi^0 \nu\overline{\nu}) < 1.4 \times 10^{-9}$$

- Best experimental limit so far comes from KTeV (1997) utilizing Dalitz decay of π^0: BR($K_L \to \pi^0 \nu\overline{\nu}$) < 5.9×10^{-7} (90% CL)
- Future experiments will utilize the $\pi^0 \to \gamma\gamma$ mode

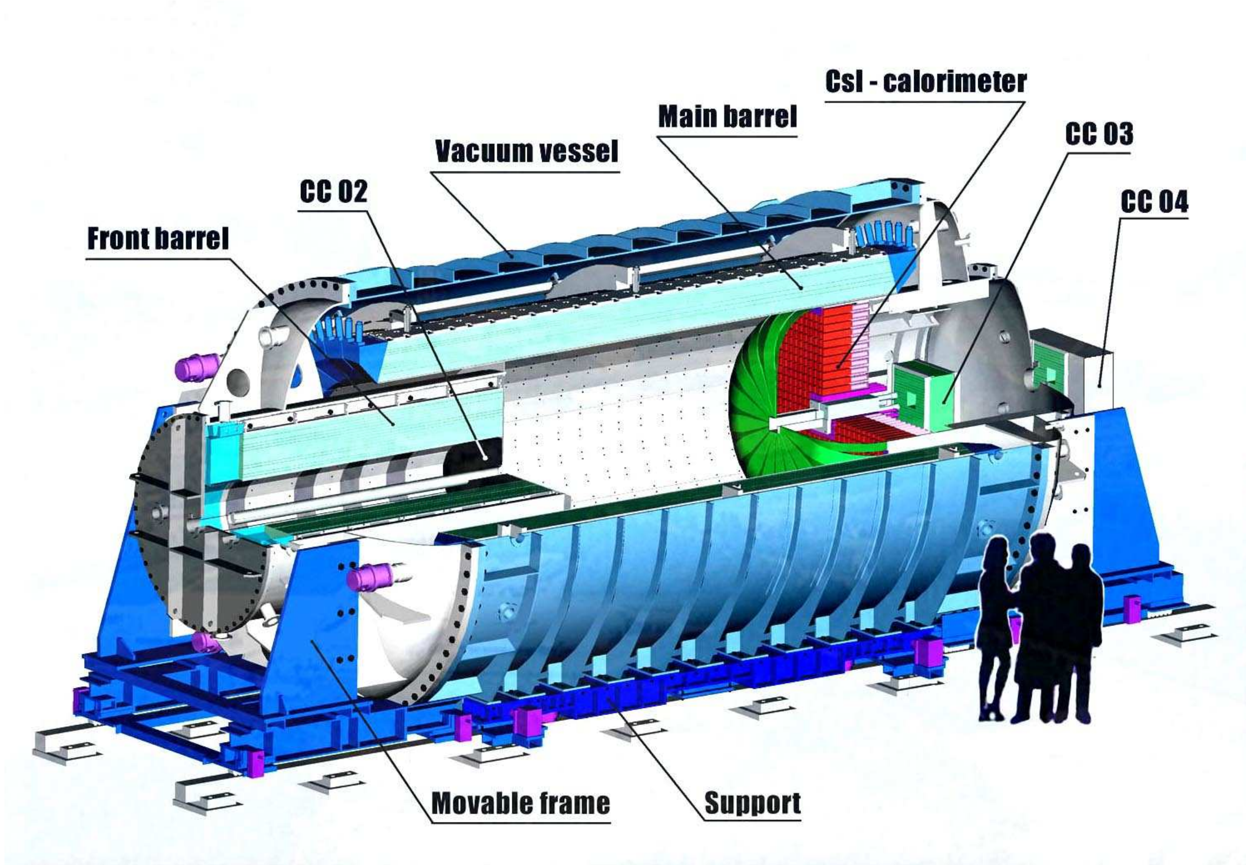


KTeV ($K_L \to \pi^0 \nu\overline{\nu}$, $\pi^0 \to \gamma\gamma$). One day test run in 1997.

- "Pencil" beam
- Background consistent with neutron interactions
- BR($K_L \to \pi^0 \nu\overline{\nu}$) < 1.6×10^{-6} (90% CL)

$K_L \to \pi^0 \nu\overline{\nu}$. KEK E391a

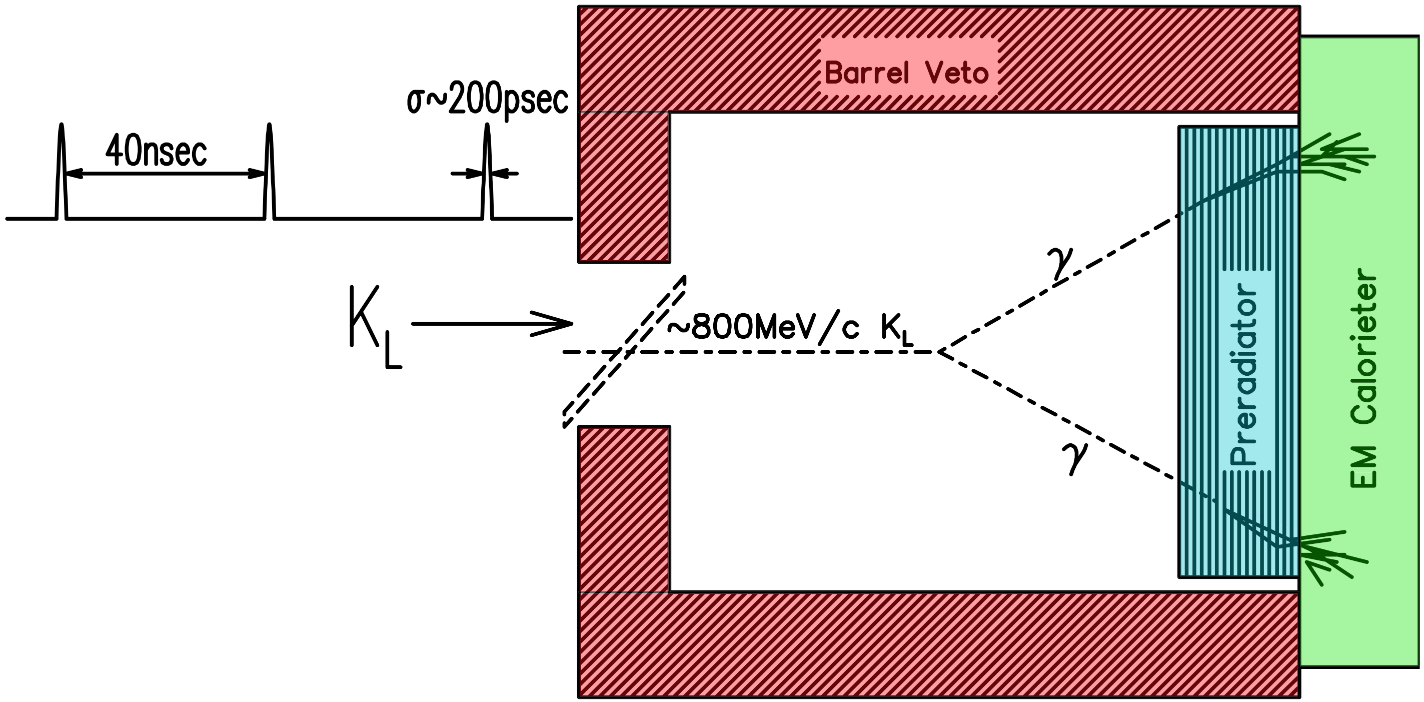
KEK E391a is the first dedicated experiment to search for $K_L \to \pi^0 \nu\overline{\nu}$.



- “Pencil” beam, high acceptance.
- Running Now! since mid-February 2004 through June. Could reach SES $\sim 4 \times 10^{-10}$ (below Grossman-Nir bound) assuming very loose photon veto cuts.
- Prototype for future experiments at e.g. JPARC. Photon veto performance will be very interesting for e.g. KOPIO.

KOPIO @ BNL

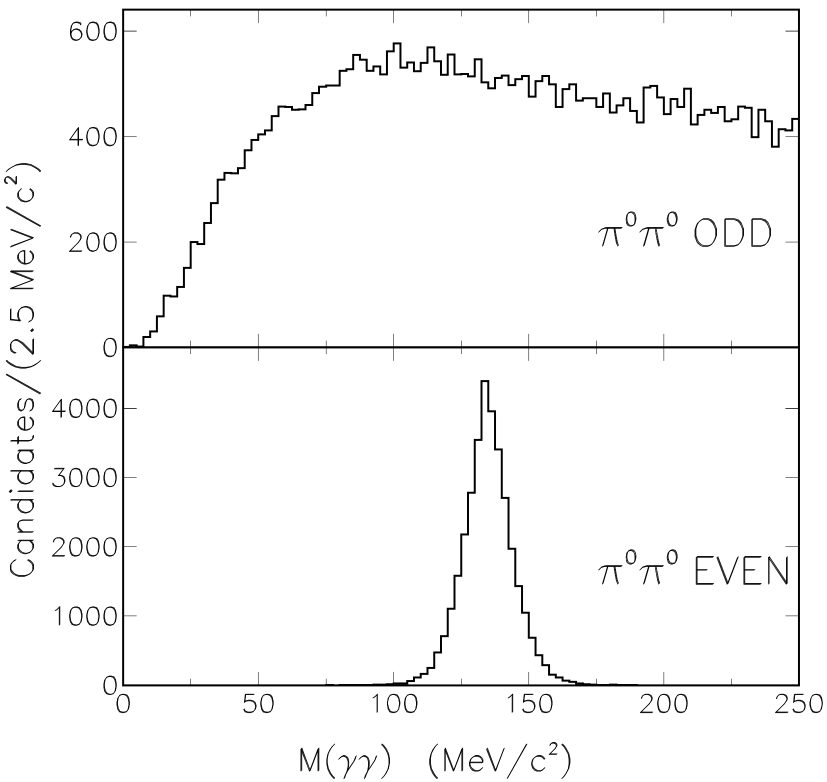
KOPIO at BNL takes a unique approach:

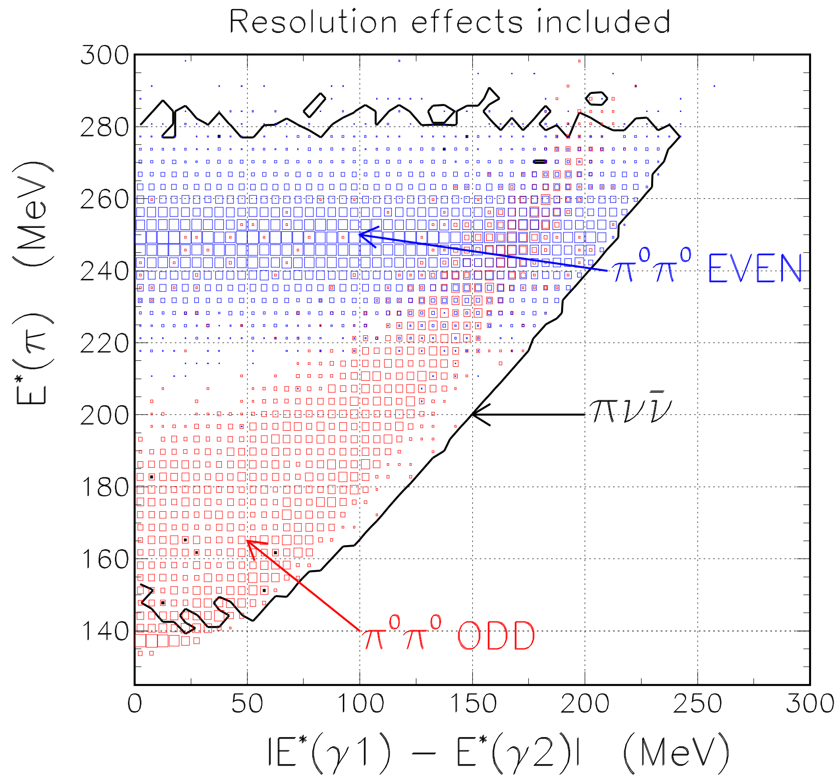


- Low energy beam. $\sim 45^\circ$ production angle. TOF to get K_L momentum
- Photon angle measurement to get K_L decay vertex and π^0 direction.
- Kinematic rejection relaxes photon veto requirements, provides redundancy needed to measure the dominant background in the signal region from data (a la E787). Full kinematic reconstruction suppresses many other backgrounds.
- Large angle production suppresses hyperons, π^0 production from beam halo neutrons

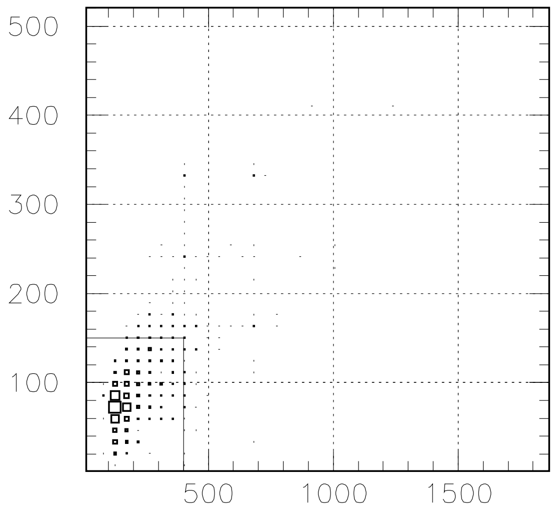
Background suppression: $K_L \to \pi^0\pi^0$

$K_L \to \pi^0\pi^0$ with 2 missing photons is the dominant background:

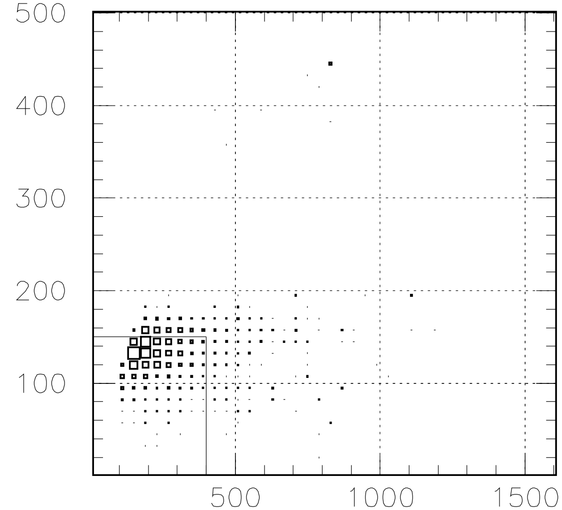




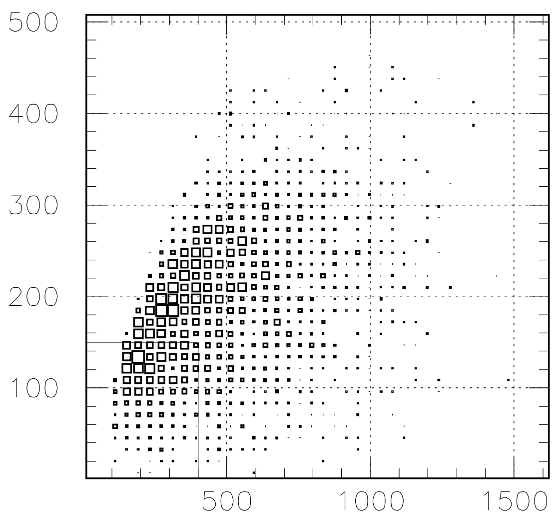
Background suppression: $K_L \to \pi^0\pi^0$



Miss−Mass vs. Miss−E (Kpi2−odd)



Miss−Mass vs. Miss−E (Kpi2−even)



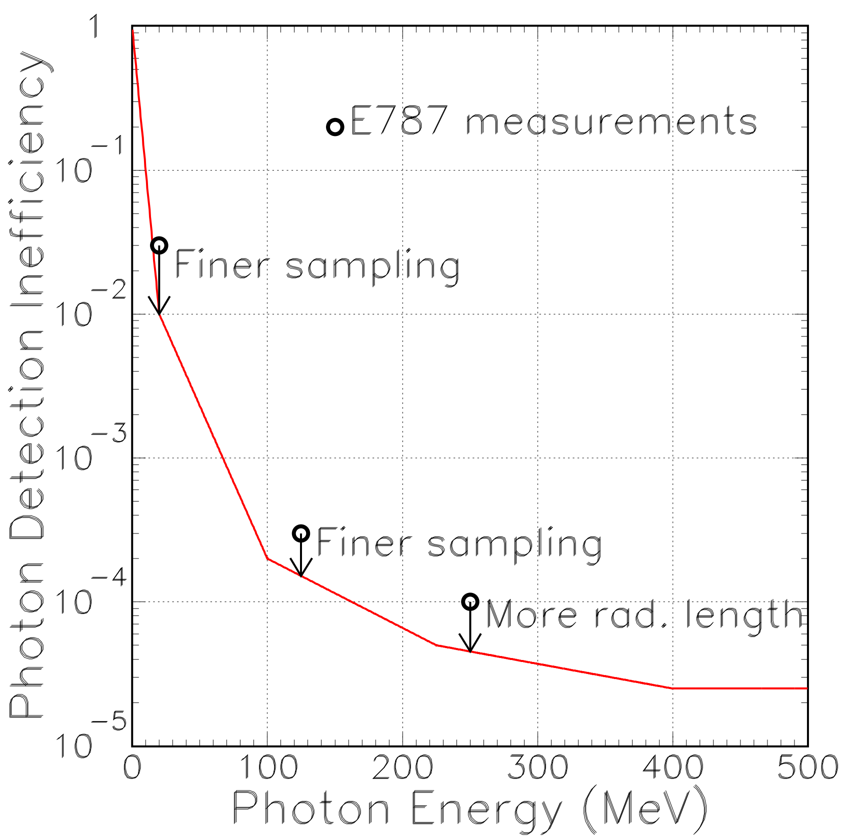
Miss−Mass vs. Miss−E (pinn)

- Missing energy cut effective in removing events where low-E γ lost.
- For asymmetric π^0 decays, cut on missing mass is effective.
  $M_{miss} \propto \sqrt{E_{miss\gamma 1} \cdot E_{miss\gamma 2}}$

Photon veto

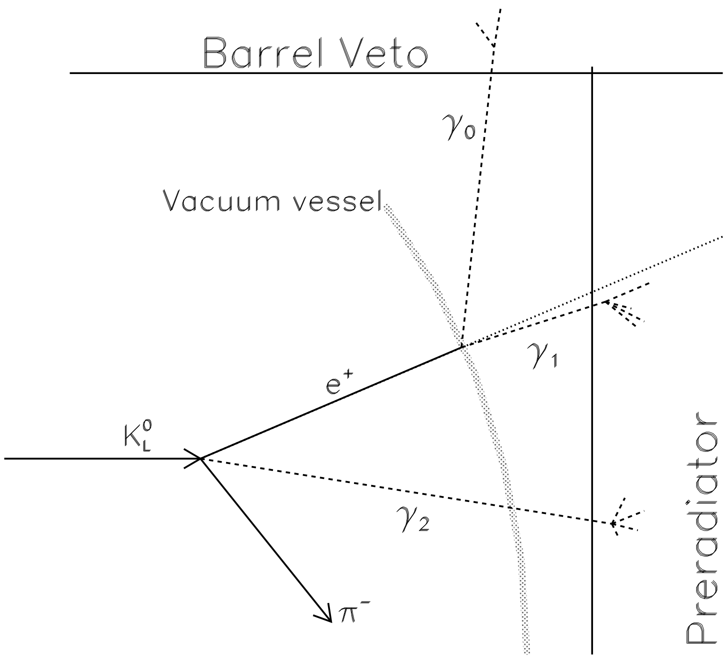
- π^0 detection inefficiency of 10^{-8} is required.
- E787 obtained $\sim 10^6$ rejection of π^0:

$$\begin{aligned} \bar{\epsilon}_\gamma &\sim 10^{-4} \quad E_\gamma = [100, 220]\mathrm{MeV} \\ &\sim 10^{-2} \quad E_\gamma = [20, 100]\mathrm{MeV} \end{aligned}$$

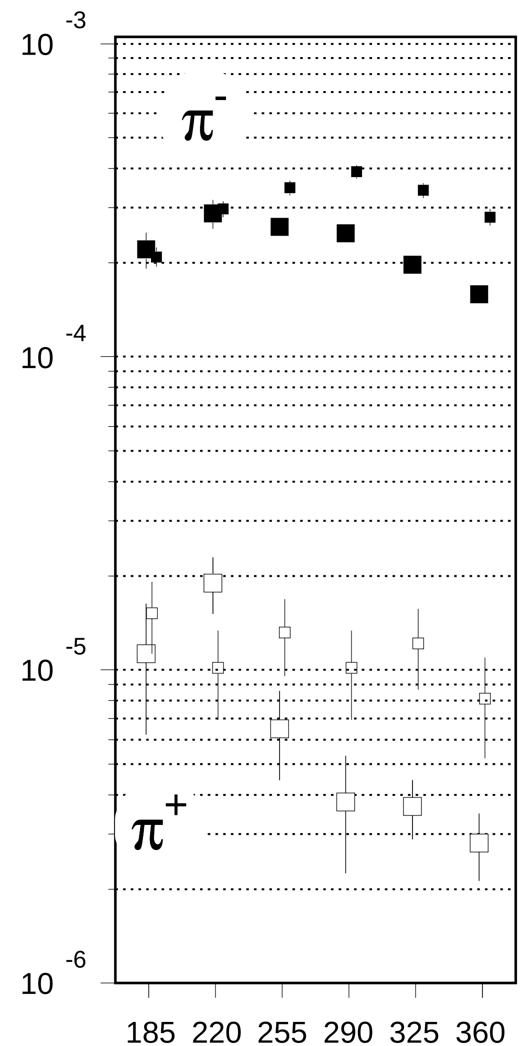


- Low energy γs in KOPIO are suppressed with cuts on missing mass/energy $\Rightarrow$ $\bar{\epsilon}_{\pi^0} < (10^{-4})(10^{-4}) = 10^{-8}$
- KOPIO goal: $\bar{\epsilon}_\gamma \sim 0.3 \times \bar{\epsilon}(787)$

Charged particle veto



Inefficiency measurements at PSI

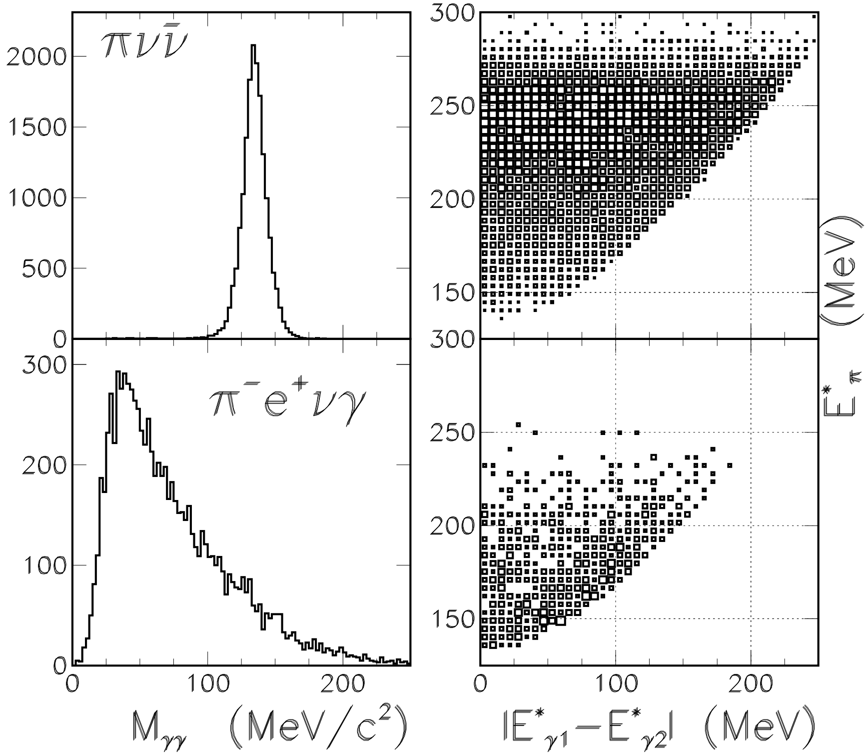


particle	e^-	e^+	π^-	π^+
ineff	$< 10^{-5}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-5}$

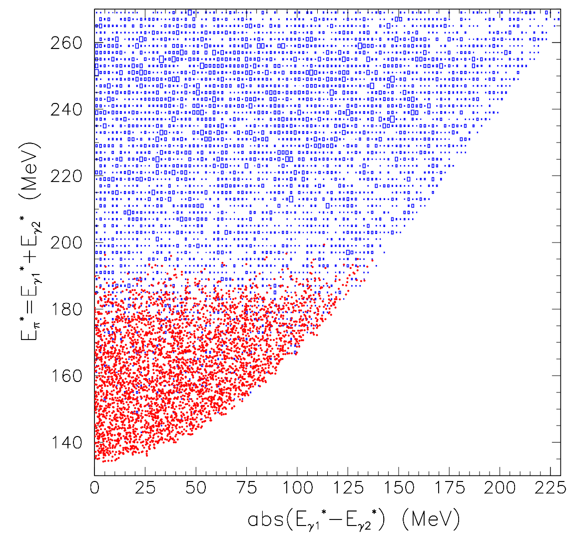
- To reach 10^{-4} for π^-, detection threshold must be $\sim 75keV$ (0.3mm of scintillator)
- Tests with scintillator sheets with direct PMT read-out reach threshold $\sim 10keV$

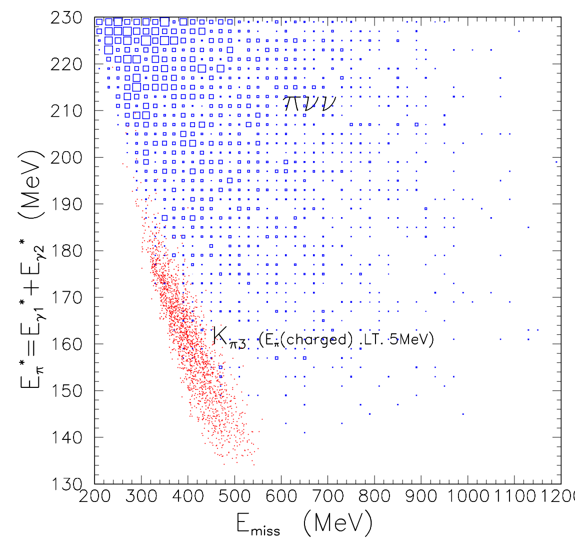
Kinematic handles on charged modes

$K_L \to \pi^\pm e^\mp \nu\gamma$:



$K_L \to \pi^+\pi^-\pi^0$:

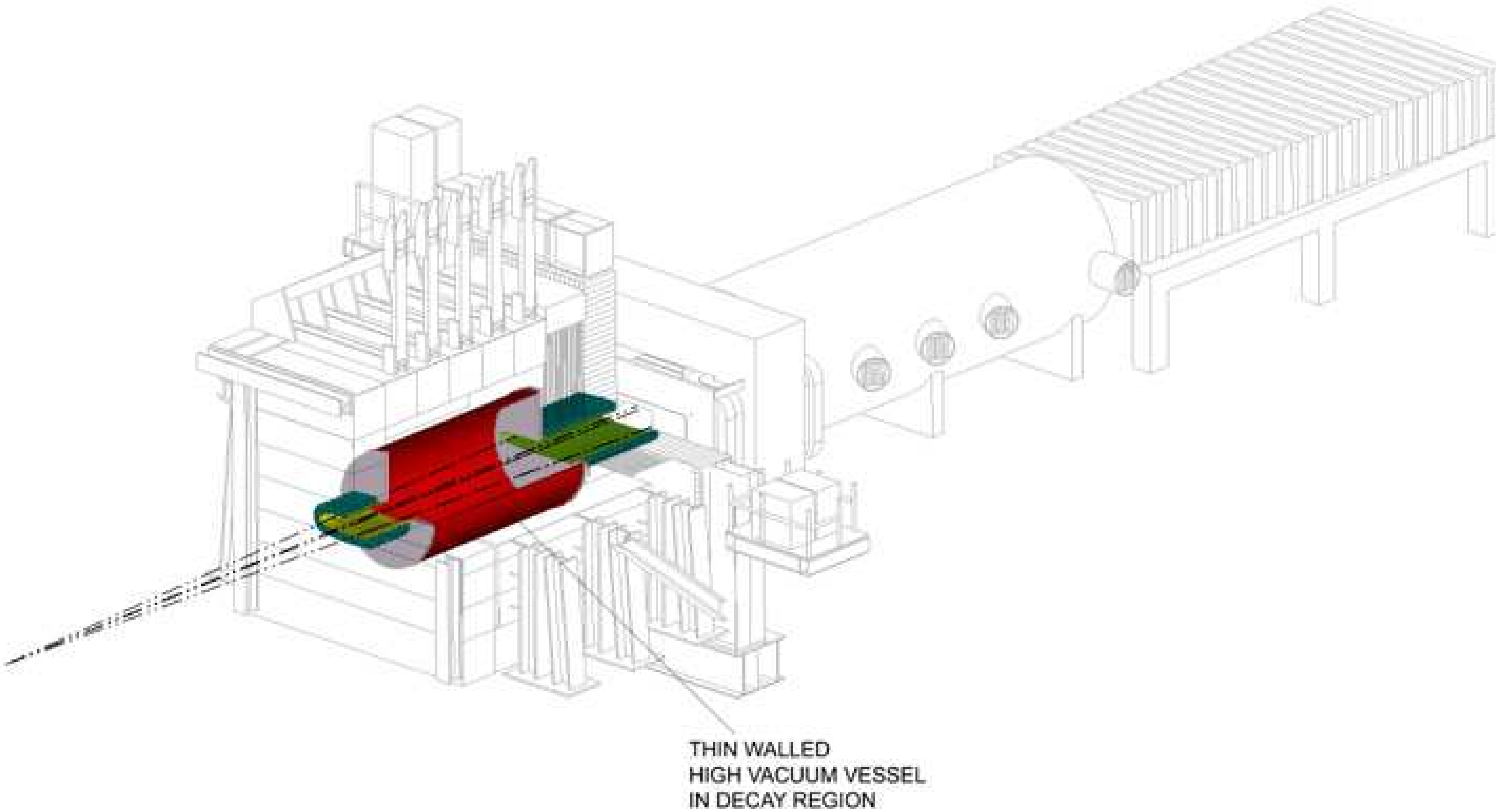


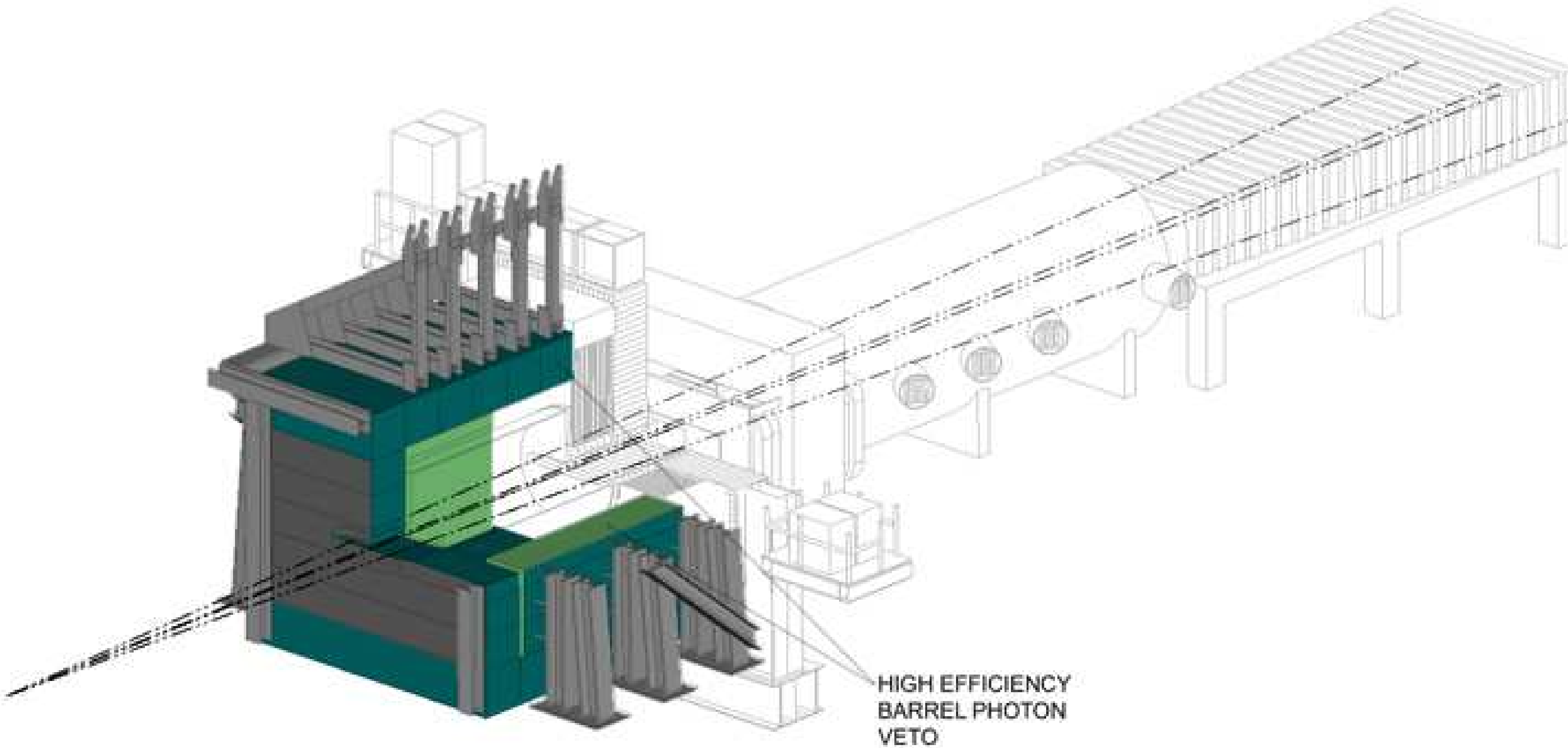


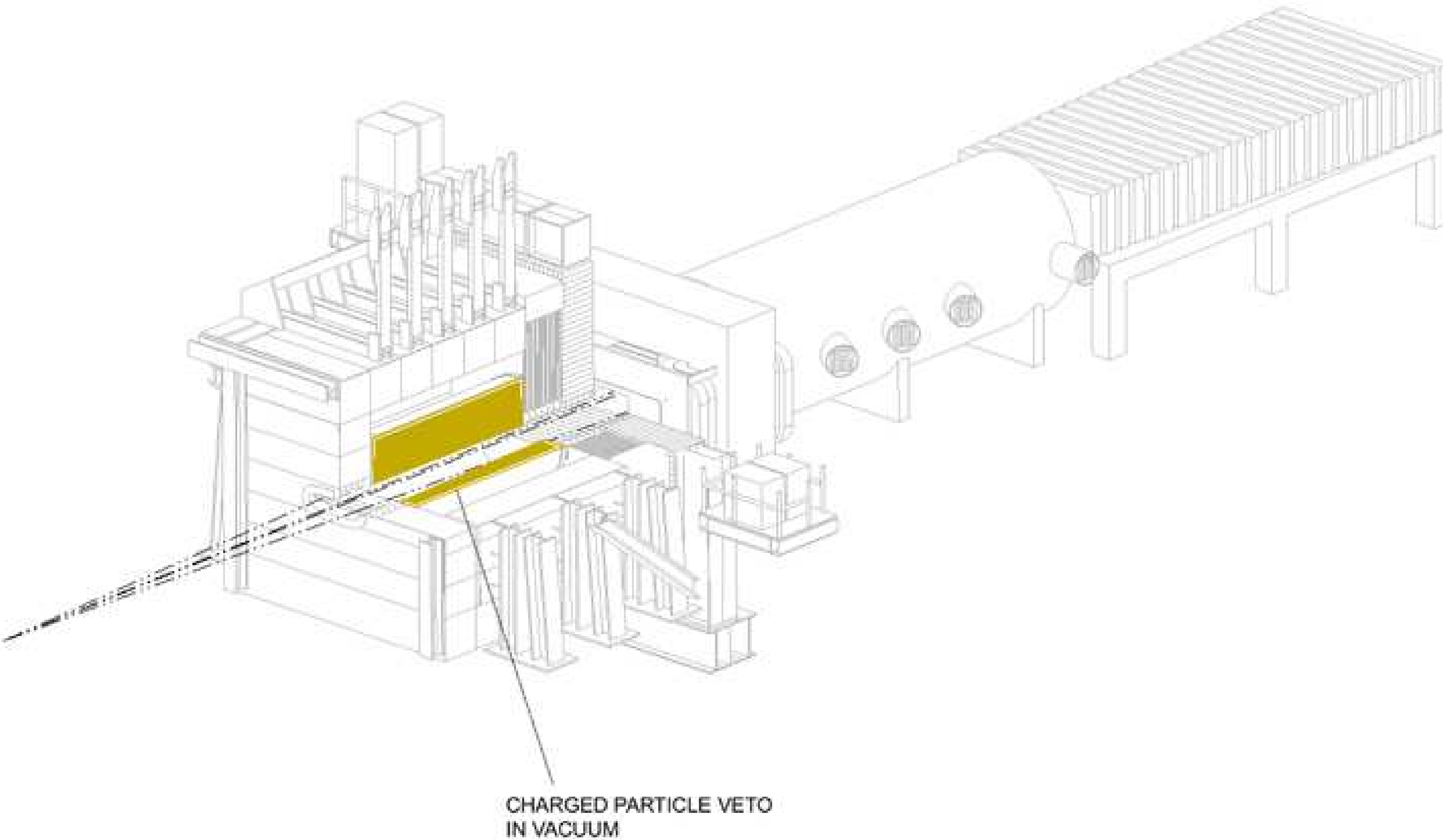
Background summary

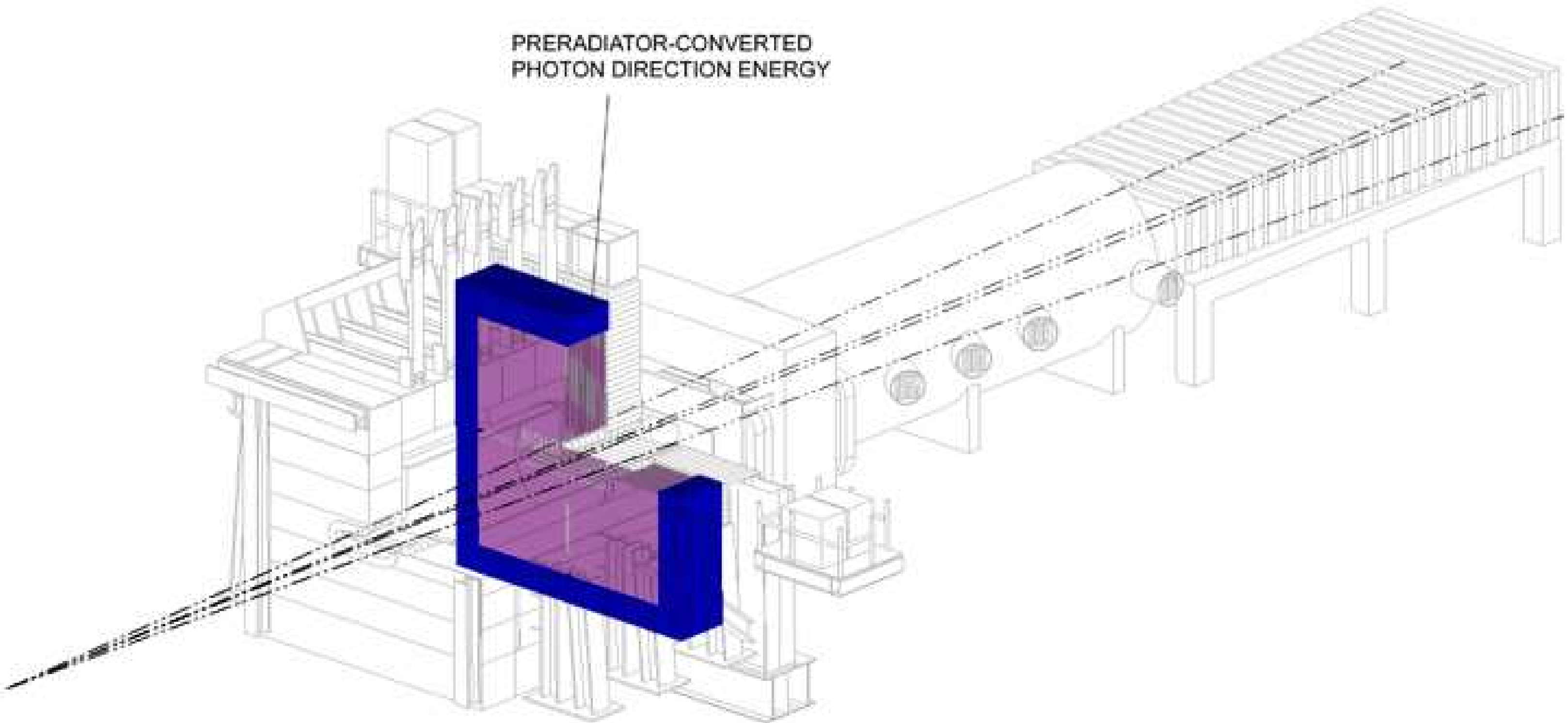
Modes	Main source	Events
$K_L \to \pi^0 \nu\overline{\nu}$ $(B = 3 \times 10^{-11})$		49
$\pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^0\gamma\gamma$	$\pi^0\pi^0$	14
$\pi^\pm l^\mp \nu\gamma,\ \pi^\pm l^\mp \nu\pi^0,\ \pi^+\pi^-\gamma$	$\pi^- e^+ \nu\gamma$	5
$\pi^+\pi^-\pi^0$		3
Other	Accidentals	1
$\gamma\gamma$		
$\pi^\pm e^\mp \nu,\ \pi^\pm \mu^\mp \nu,\ \pi^+\pi^-$		
$\Lambda \to \pi^0 n,\ \Sigma^+ \to \pi^0 p,\ K^\pm \to \pi^\pm \pi^0$		
Interactions: n,K_L, γ		
Accidentals: n,K_L, γ		
Total background		23

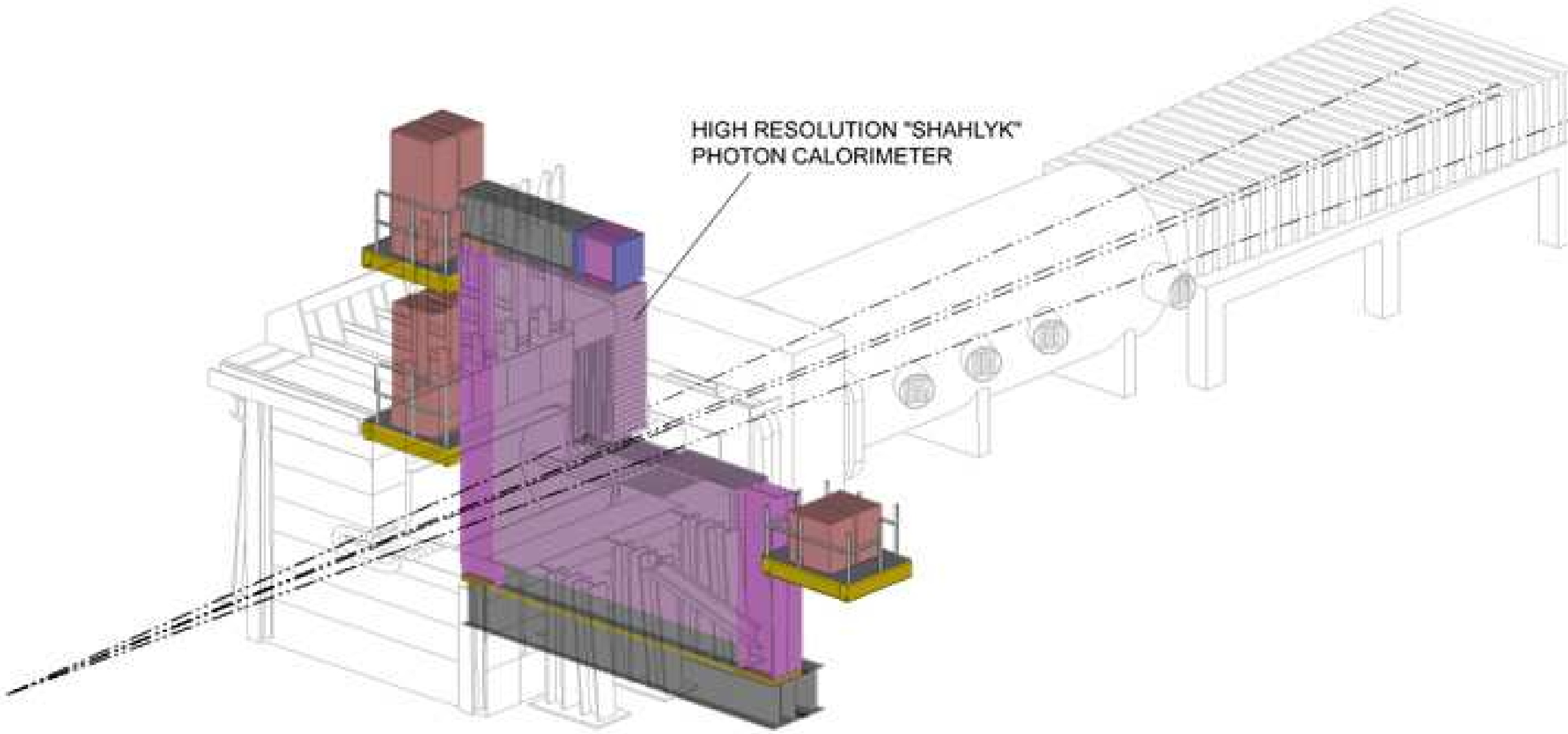
- Acceptance: 9×10^{-3}
- 9600 hours

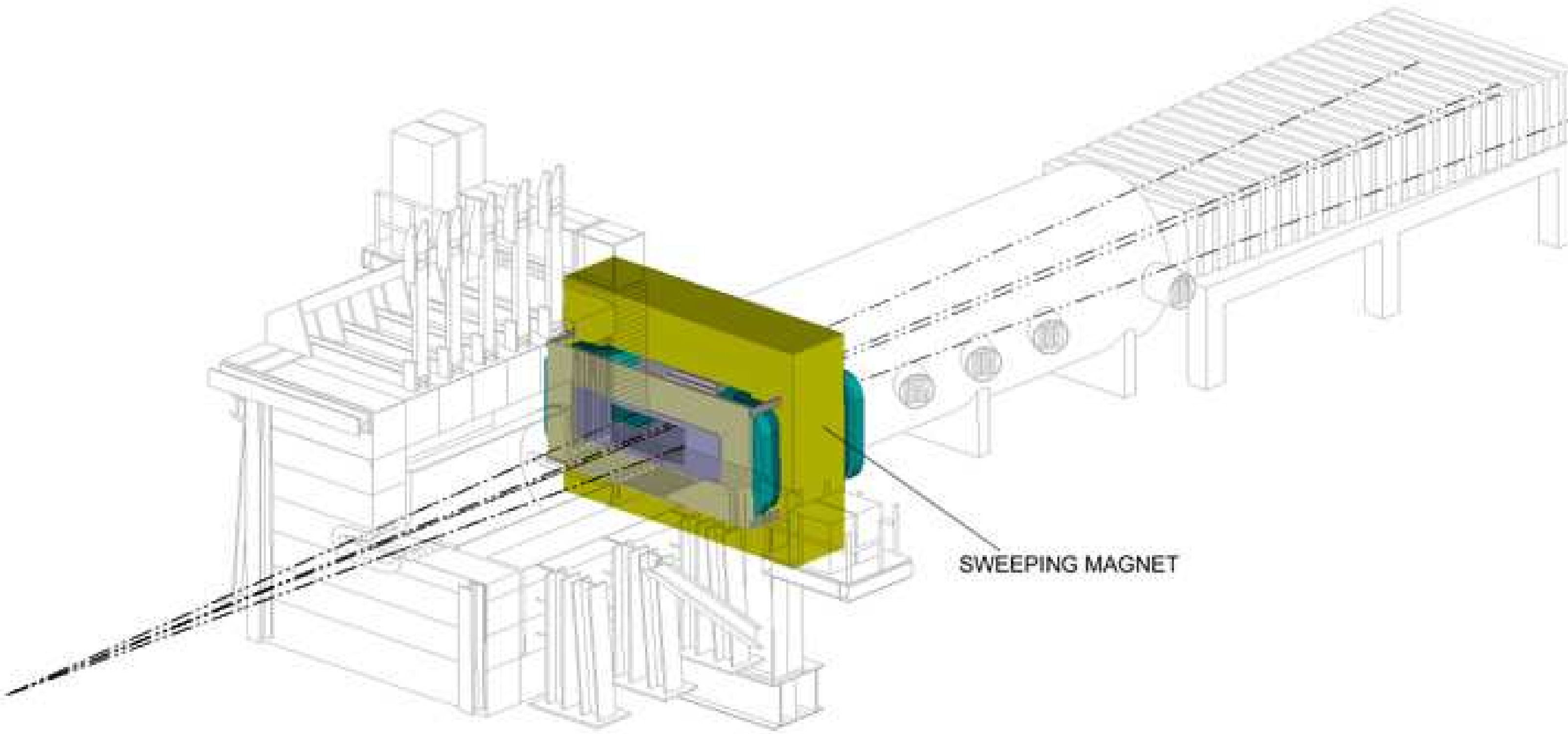

THIN WALLED
HIGH VACUUM VESSEL
IN DECAY REGION

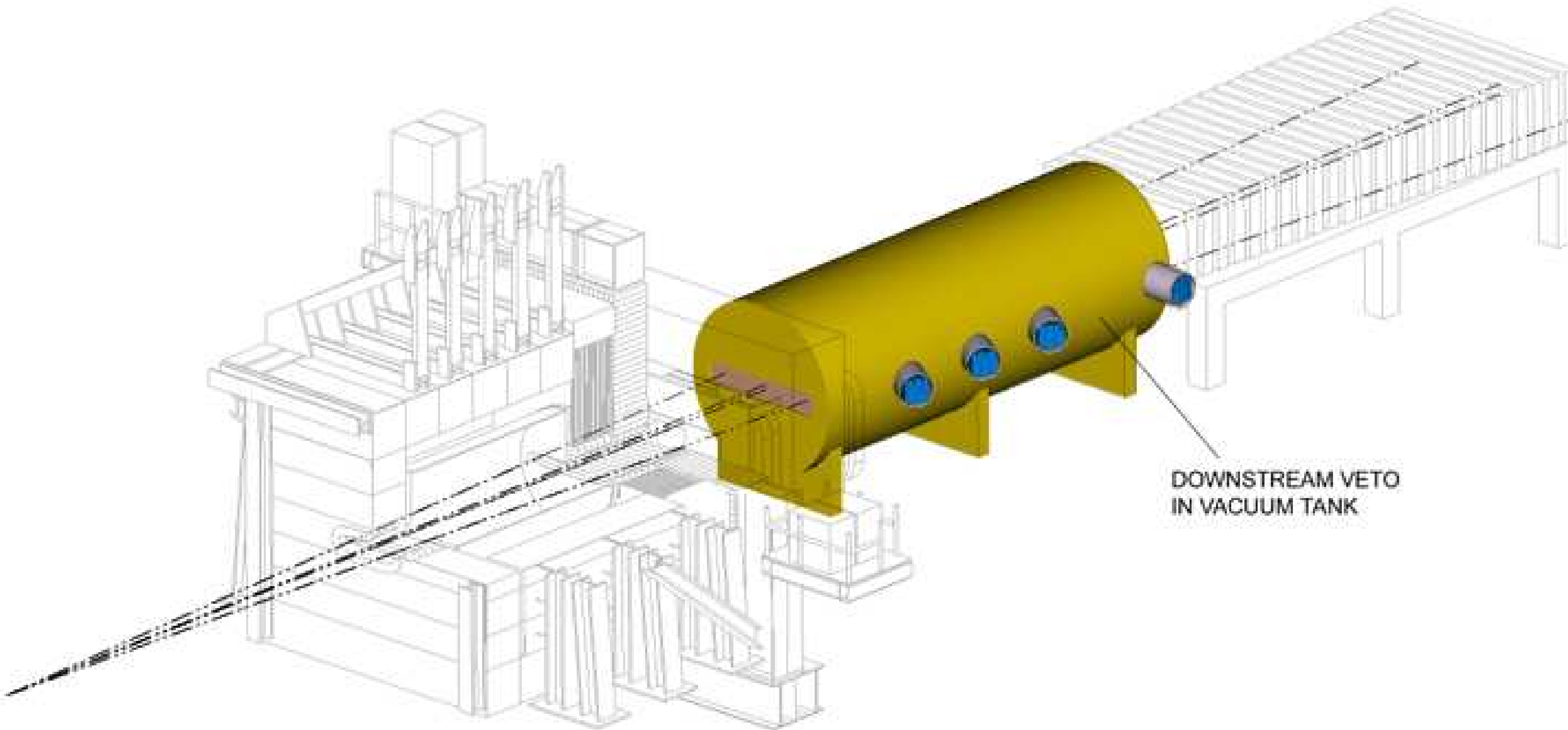

HIGH EFFICIENCY
BARREL PHOTON
VETO

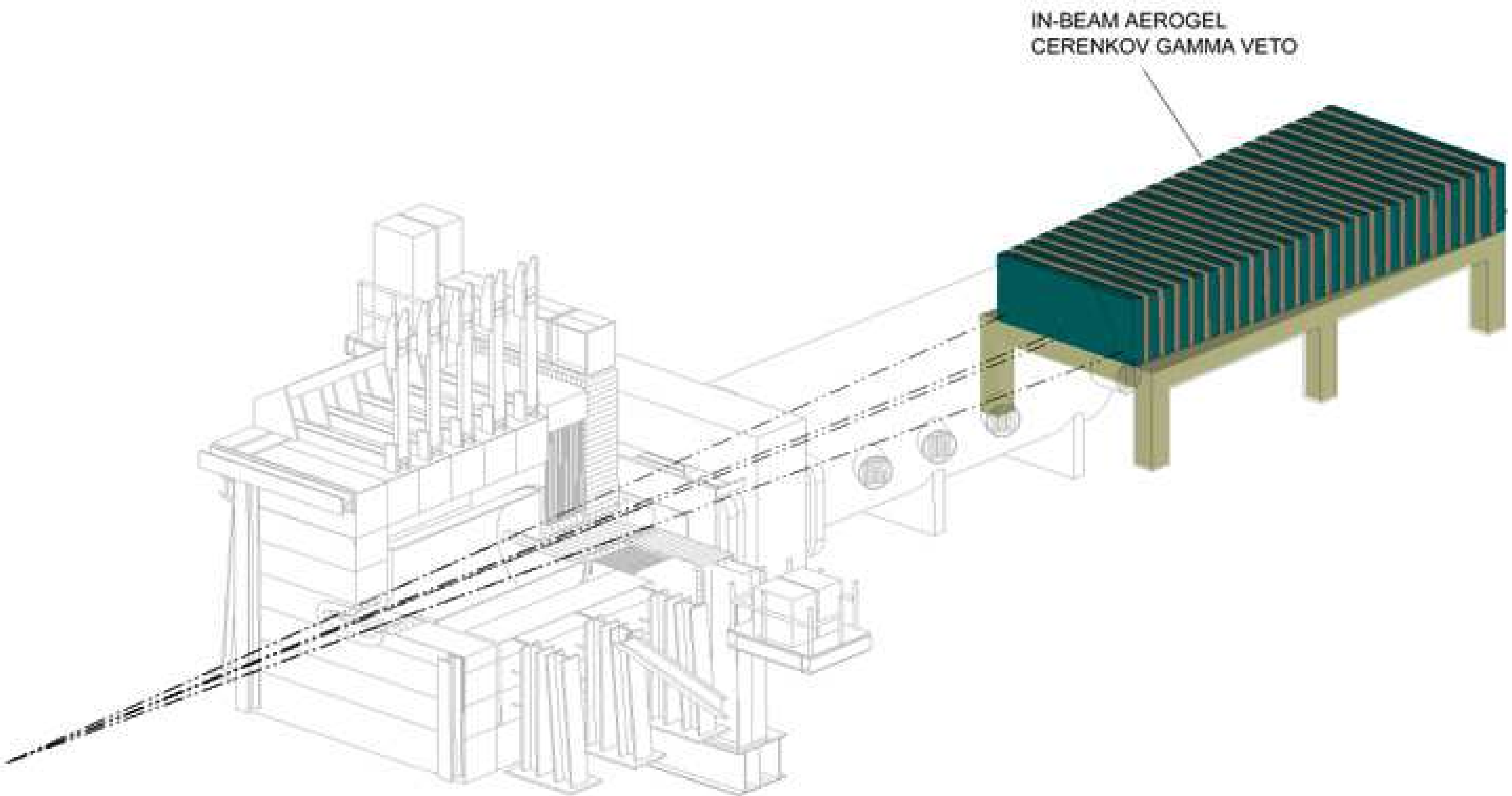

CHARGED PARTICLE VETO
IN VACUUM


PRERADIATOR-CONVERTED
PHOTON DIRECTION ENERGY


HIGH RESOLUTION "SHAHLYK"
PHOTON CALORIMETER


SWEEPING MAGNET


DOWNSTREAM VETO
IN VACUUM TANK

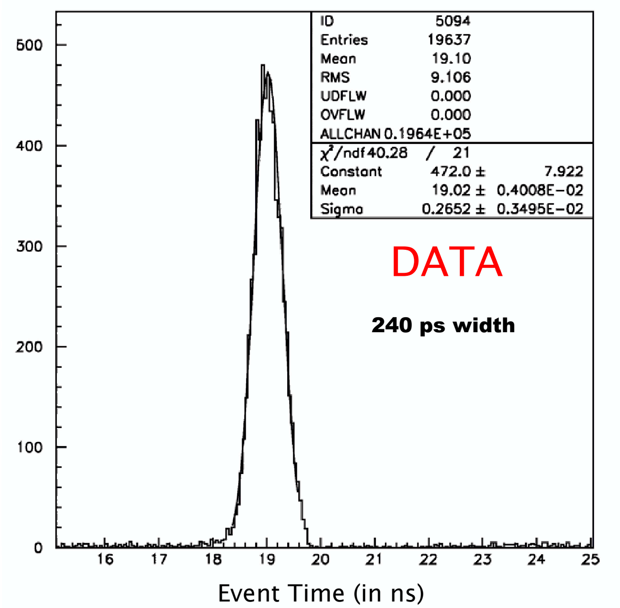

IN-BEAM AEROGEL
CERENKOV GAMMA VETO

Beam

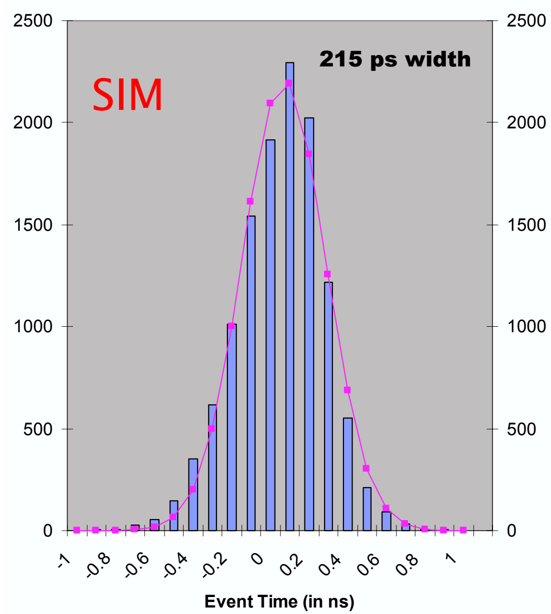
- Proton beam
  - 100×10^{12} protons per 2.7 sec spill; 5 sec cycle time; needs AGS injection energy upgrade
  - $p \sim 25$ GeV/c
  - Slow extraction with micro-bunching ($\sigma = 200ps$ every 40 ns)
  - Interbunch extinction $\sim 10^{-3}$
- K_L beam
  - $\sim 45^\circ$ production angle
  - Low energy “pancake” beam: [0.5,1.5] GeV, $5mr \times 100mr$
  - $\sim 10^8 K_L$ per spill, 12% decay
  - $\sim 10^{11}$ neutrons per spill
  - Vacuum $\sim 10^{-7}$ Torr

Microbunching: bunch width

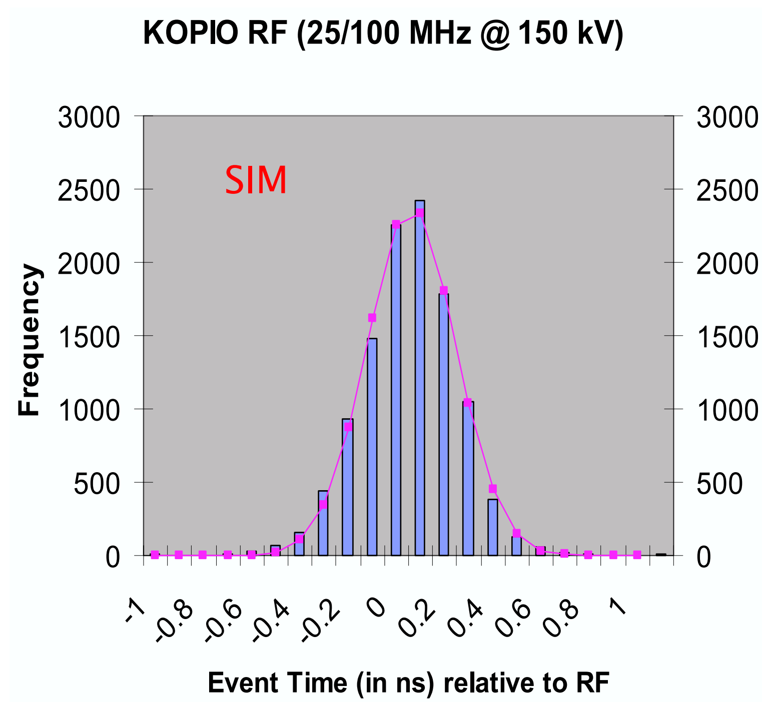
93 MHz data



93 MHz simulation

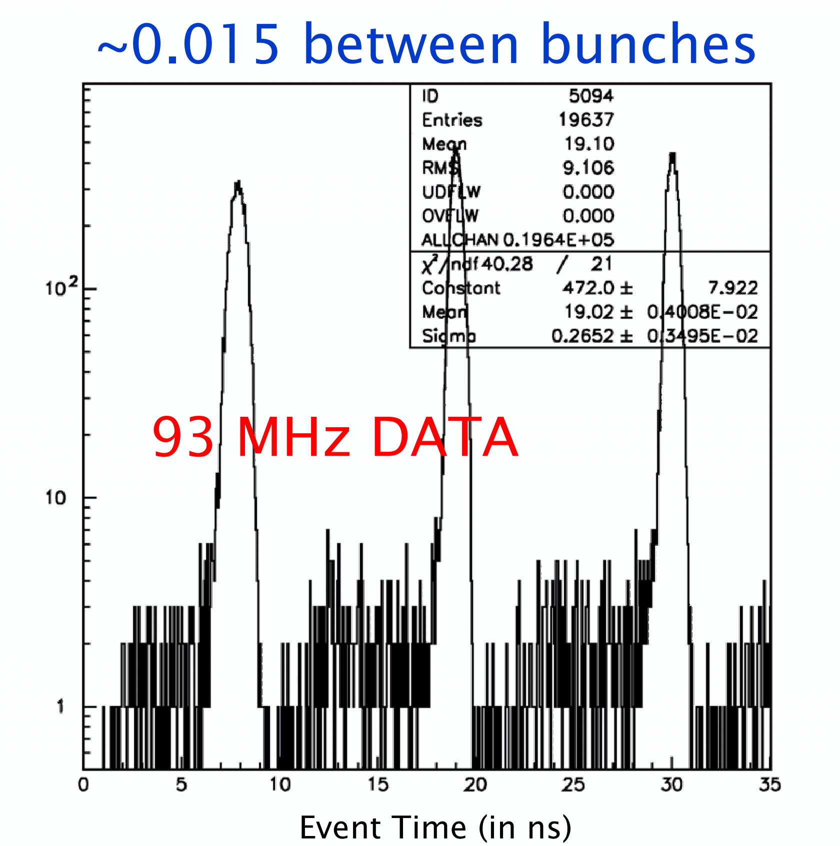


KOPIO Simulation (185ps width)



- Beam tests of microbunching have been done with a 93MHz RF cavity.
- KOPIO: 25 MHz cavity to get 40ns microbunch spacing and 100 MHz cavity to get the microbunch width

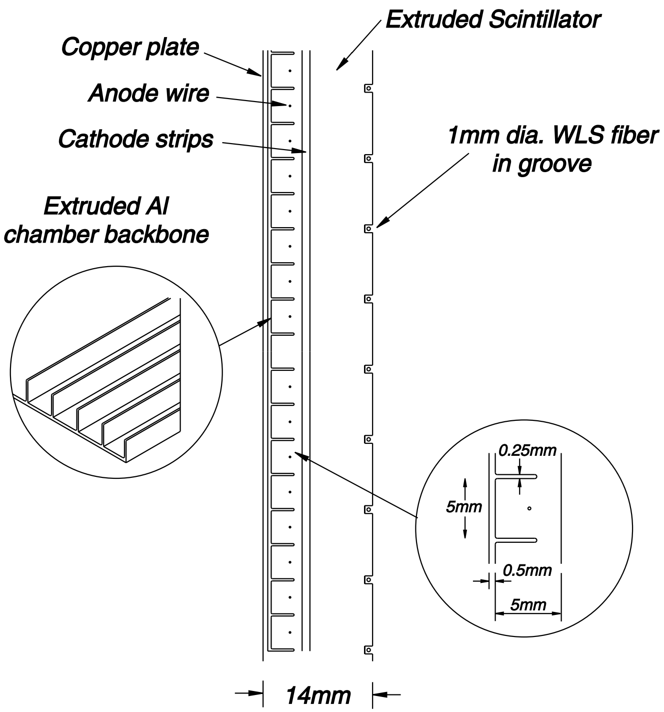
Microbunching: interbunch extinction



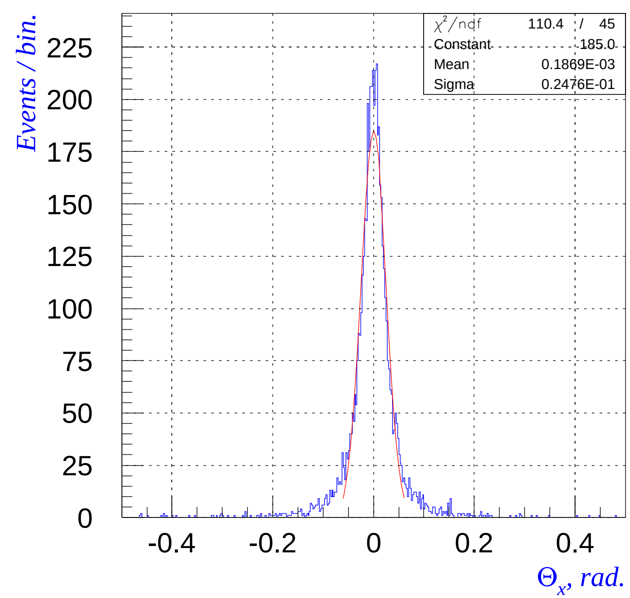
- Extinction of $\sim 10^{-3}$ desired
- Need to control power supply ripple
- New test beam run just completed:
  - Improved systematics ($\overline{p}$ beam)
  - Bunch width/extinction measured in a matrix of RF frequency, RF voltage and $\frac{\Delta p}{p}$
  - Offline data analysis and comparisons to 4D simulation in progress

Preradiator

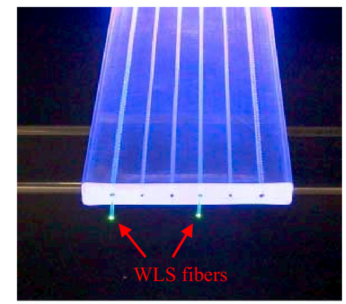
- Track $\gamma \rightarrow e^+e^-$ early in the shower. $\sigma_\theta \sim 25mr$ needed.
- $\sim 0.03X_0$ per layer. $2X_0$ in total.
- In progress: full scale prototypes, HV and readout electronics, scintillator production, full mechanical design

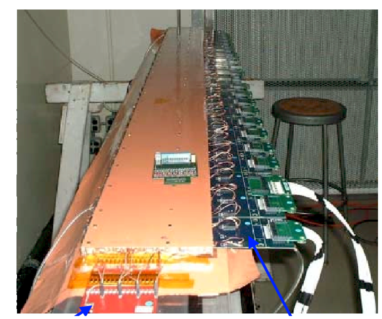


Photon beam. Prototype chamber.



Θ_x distribution of detected photons. E_γ = 250 MeV.

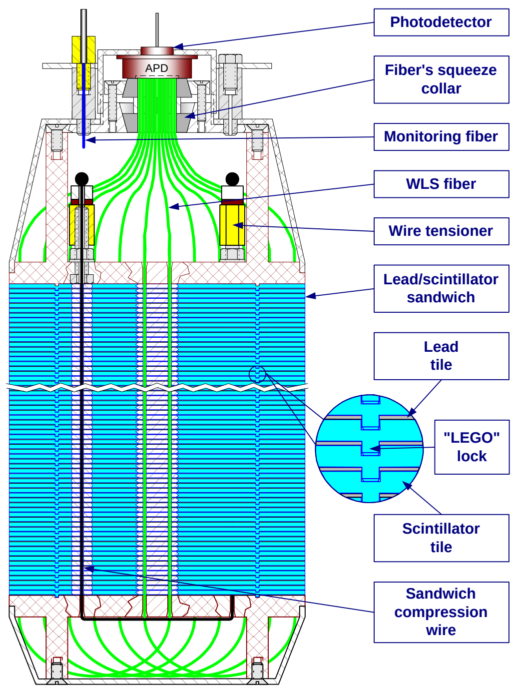




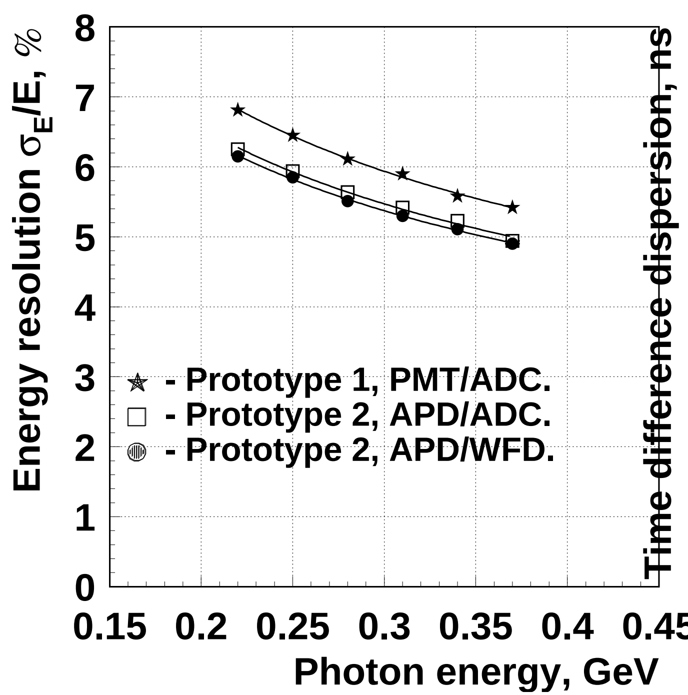
Shashlyk Calorimeter

- $16X_0$ (18 including preradiator)
- Photon beam test results:
  - $\frac{\sigma_E}{E} = \frac{(2.9\pm0.1)\%}{\sqrt{E(GeV)}}$
  - $\sigma_t = \frac{90\pm10ps}{\sqrt{E(GeV)}}$
- In progress: full mechanical design, HV and readout electronics, monitoring system, APD cooling system

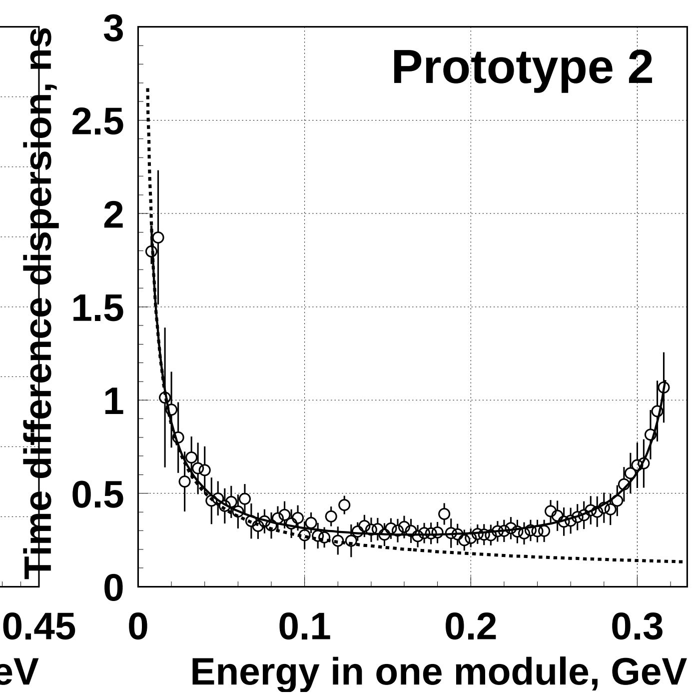
Shashlyk module



Energy resolution



Timing resolution



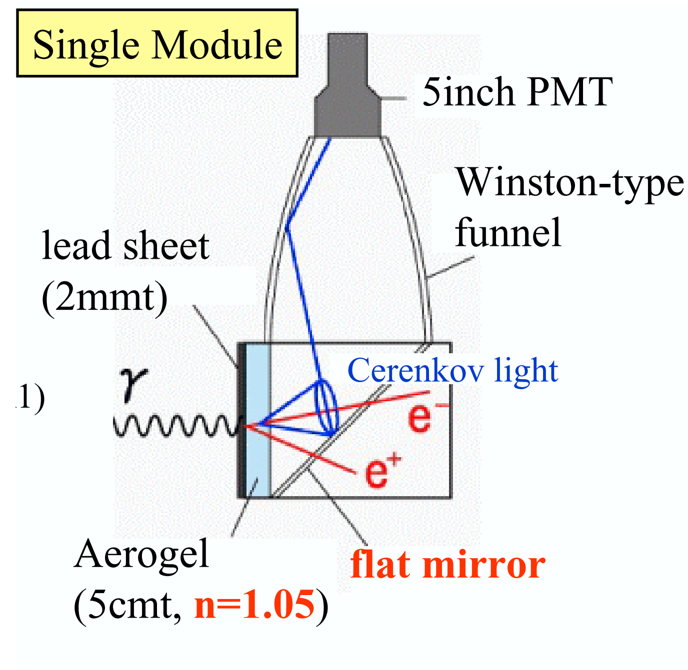
Catcher

Requirements:

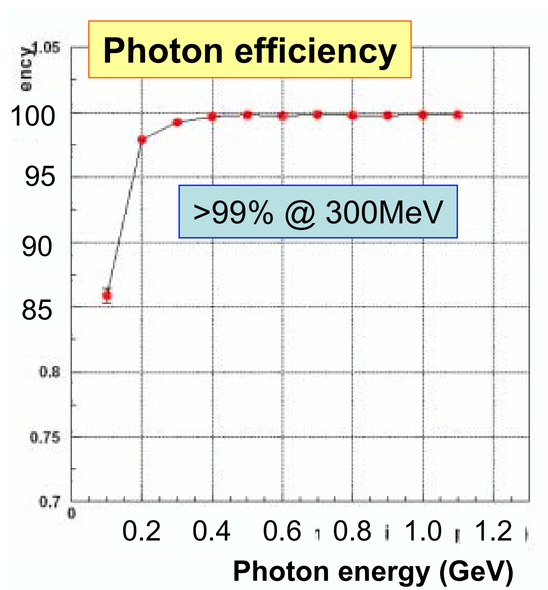
- Photon efficiency $>$ 98.5% at 300 MeV
- Neutron sensitivity $<$ 0.2% at 800 MeV

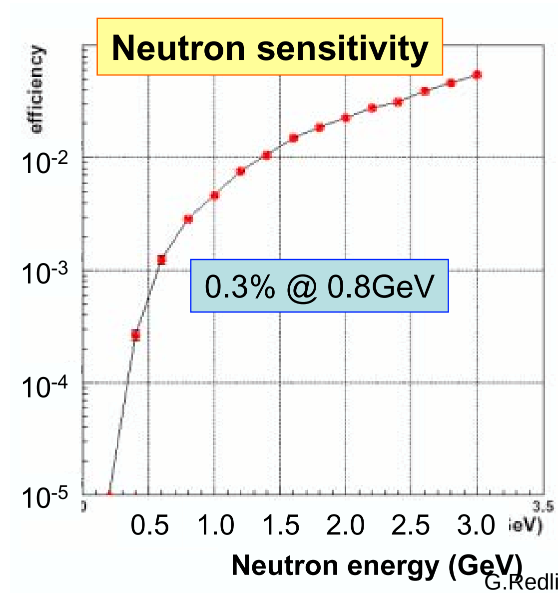
This year:

- Charged beam test of prototype module
- Light yield as a function of position, incident angle



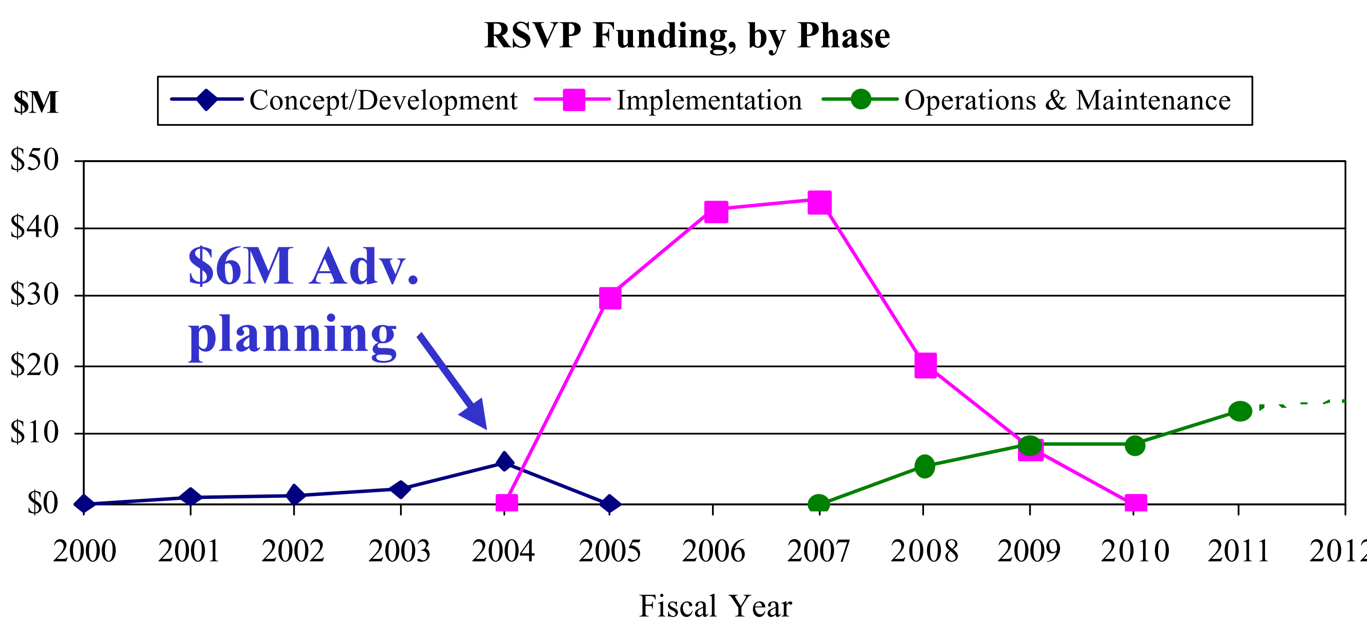
Simulation:





Outlook

- E949 detector is working well. Analysis of data on $K^+ \to \pi^+ \nu\overline{\nu}$ (above $K^+ \to \pi^+\pi^0$ peak) completed. Central value of BR remains high, but needs more statistics.
- DOE had approved running E949 for 60 weeks, but terminated the program after 12 weeks. Proposal submitted to NSF to run E949 during RSVP construction phase.
- KOPIO R&D phase is winding down. Key features of the concept have been established. Advanced planning for the construction phase is beginning.
- The RSVP program (KOPIO: $K_L \to \pi^0\nu\overline{\nu}$ and MECO: $\mu^- N \to e^- N$) was included in the FY04 President's Budget request for a 2005 construction start.
- J. Whitmore (NSF) presentation at BNL (May 04)



Outlook

- Although focus has been on the “dynamic duo”, other kaon experiments have been discussed for the AGS.
  - E923: μ polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu$ (T-violation)
  - E927: Precision measurement of $K^+ \rightarrow \pi^0 e^+ \nu \quad (|V_{us}|)$
  - μ polarization in $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ and $K_L \rightarrow \pi^0 \mu^+ \mu^- \quad (V_{td})$
- L. Littenberg: “interesting AGS capabilities facilitate new ideas”
  - High intensity beams
  - Microbunching
  - Low energies (TOF, stopped K, stopped μ)